Entanglement Without Signaling: EPR, ER=EPR, It from Qubit, Quantum Computers, and the Non-Communication Boundary of Emergent Spacetime

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Entanglement is one of the most experimentally secure and conceptually disruptive facts in physics, yet its meaning remains unsettled at the boundary between quantum information, relativity, and quantum gravity. From the 1935 EPR paradox to Bell inequality violations, quantum theory has forced physics to accept correlations stronger than any local classical account can explain. At the same time, the Non-Communication Theorem prevents these correlations from becoming faster-than-light messages, preserving causal order even while undermining naive locality. Recent developments, including ER=EPR, holographic quantum error correction, traversable-wormhole protocols, attosecond studies of entanglement formation, and quantum-computer simulations of SYK-like dynamics, suggest a deeper synthesis: spacetime geometry may not be fundamental, but may emerge from structured entanglement. This paper examines whether "It from Qubit" can become more than metaphor, asking what would count as quantum instantiation of emergent geometry in actual physical systems. The central thesis is that quantum computers may become laboratories for holographic spacetime, but any viable theory must remain bounded by non-communication.

Keywords: EPR paradox, ER=EPR, It from Qubit, Non-Communication Theorem, quantum entanglement, Bell inequality, quantum teleportation, holography, AdS/CFT, SYK model, traversable wormhole, quantum computer, emergent spacetime, quantum gravity, holographic quantum error correction, attosecond entanglement, black hole information, quantum simulation.

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Outline

1. The Problem: Entanglement, Reality, and Communication

1.1 The central question

1.2 Why entanglement is not ordinary correlation

1.3 Why the communication question matters

1.4 The working distinction: correlation, causation, and signaling

1.5 Thesis of the paper

2. EPR: The 1935 Origin of the Nonlocality Problem

2.1 The Einstein-Podolsky-Rosen argument

2.2 Completeness, locality, and elements of reality

2.3 Einstein's objection to "spooky action at a distance"

2.4 The difference between instantaneous update and physical signal

2.5 EPR as the seed of the modern entanglement problem

3. Bell Tests and the Direct Experimental Reality of Entanglement

3.1 Bell's theorem and the failure of local hidden variables

3.2 The CHSH inequality: S <= 2

3.3 Quantum violation: S up to 2*sqrt(2)

3.4 Loophole-free Bell tests

3.5 What Bell experiments prove and do not prove

4. The Non-Communication Theorem as the Causal Boundary

4.1 Statement of the theorem

4.2 Reduced density matrices and local randomness

4.3 Alice cannot signal by choosing a measurement basis

4.4 Bob's local state remains unchanged

4.5 Why classical comparison is required

4.6 How NCT preserves relativity while allowing nonclassical correlation

5. Quantum Teleportation: Entanglement Plus Classical Information

5.1 Why teleportation is not faster-than-light travel

5.2 The role of shared entanglement

5.3 The role of Alice's classical bits

5.4 Bob's correction operation

5.5 Teleportation as an operational demonstration of NCT

6. Attosecond Entanglement Formation: Time Structure Without Signaling

6.1 The 232 attosecond helium result

6.2 Local formation of electron-ion entanglement

6.3 Why this is not a distance-dependent EPR delay

6.4 Birth-time structure, wave packets, and interelectronic coherence

6.5 The distinction between formation time and communication time

7. ER=EPR: Entanglement as Geometric Connection

7.1 The 1935 pairing of EPR and Einstein-Rosen bridges

7.2 Maldacena and Susskind's 2013 conjecture

7.3 Entangled black holes and non-traversable bridges

7.4 Why ER=EPR does not violate NCT

7.5 The bridge as geometry, not a free communication channel

7.6 What remains conjectural

8. Holography and the Geometry of Quantum Information

8.1 AdS/CFT as the organizing framework

8.2 Eternal AdS black holes and thermofield double states

8.3 Ryu-Takayanagi entropy and area from entanglement

8.4 Entanglement wedge reconstruction

8.5 Holographic quantum error correction

8.6 Geometry as an encoded informational structure

9. It from Qubit: From Quantum Information to Spacetime

9.1 Wheeler's "It from Bit" and the quantum revision

9.2 Why qubits are not merely abstract bookkeeping

9.3 What it means for "It" to arise from entanglement

9.4 Emergence versus simulation

9.5 Bulk reality as an operational description

9.6 The proposed hierarchy: qubit, code, geometry, causality

10. Quantum Computers as Laboratories for Emergent Spacetime

10.1 Quantum processors as physical instantiators

10.2 SYK-like models and holographic chaos

10.3 Traversable-wormhole-inspired teleportation

10.4 Lessons from the 2022 quantum-processor experiment

10.5 Criticisms: small size, hand-tuning, and weak chaos

10.6 What larger quantum simulations must demonstrate

11. Criteria for Quantum Instantiation Into Actual Reality

11.1 Real entanglement

11.2 Dynamical implementation

11.3 Scrambling and operator growth

11.4 Error-correcting bulk reconstruction

11.5 Area-like entanglement behavior

11.6 Scaling beyond toy models

11.7 Independent observables and falsifiability

11.8 Compatibility with NCT

12. Future Developments: What Would Count as Progress

12.1 Larger and less engineered holographic simulations

12.2 Error-corrected quantum processors

12.3 Gravity-mediated entanglement experiments

12.4 Complexity growth and black-hole interiors

12.5 Testing whether geometry is emergent or merely interpretive

12.6 Why NCT remains the boundary condition

12.7 Final synthesis: entanglement can build geometry, but not a forbidden message

13. References

Art

1. The Problem: Entanglement, Reality, and Communication

1.1 The central question

The central question of this paper is whether quantum entanglement is merely a strange correlation between separated systems, or whether it reveals something deeper about the structure of reality itself. Since the EPR argument of 1935, physics has had to confront a profound tension: quantum theory predicts correlations between distant systems that cannot be explained by ordinary local classical causes, yet those correlations cannot be used to transmit messages faster than light. This combination is conceptually unstable for any worldview that expects reality to be built from localized objects carrying definite properties through space and time. Entanglement says that the whole may possess a quantum state that is not reducible to independently existing parts. Relativity says that causal communication must respect light-cone structure. The Non-Communication Theorem says that these two demands can coexist: quantum correlation may be nonclassical, but controllable signaling remains causal.

The deeper problem arises when entanglement is no longer treated as a rare laboratory curiosity, but as a candidate foundation for spacetime geometry. ER=EPR proposes that entanglement and geometric connection may be two descriptions of the same underlying structure. It from Qubit extends this intuition by suggesting that spacetime, gravitation, and perhaps locality itself may arise from quantum information. Quantum computers now make this question experimentally sharper. If a quantum processor physically instantiates entangled many-body dynamics whose best description is holographic geometry, then the boundary between simulation and realization becomes less obvious. The question becomes: when does a quantum computation merely represent a geometry, and when does it instantiate the quantum informational substrate from which geometry emerges?

1.2 Why entanglement is not ordinary correlation

Ordinary correlation is compatible with pre-existing local facts. If two gloves are separated into two boxes and one box is sent to Alice while the other is sent to Bob, Alice's discovery of a left-handed glove immediately tells her that Bob has the right-handed glove. Nothing mysterious has happened. The correlation was created at the source, carried by the objects, and revealed by measurement. Quantum entanglement is different. In an entangled state, the joint system may have definite relational structure even when the individual subsystems do not possess definite values for the measured properties prior to measurement.

This is why entanglement cannot be reduced to ignorance about hidden ordinary variables. Bell's theorem and Bell-type experiments show that no theory preserving both locality and predetermined classical values can reproduce the full pattern of quantum correlations.

Entanglement is therefore not merely incomplete knowledge about two separated objects. It is a nonclassical structure of the joint state.

For a maximally entangled pair, the total state may be pure while each local subsystem appears maximally random. In symbolic form, the whole may be described by a state such as:

|Phi+> = (|00> + |11>)/sqrt(2)

Yet the local state available to either observer alone is random. Alice sees no message in her results. Bob sees no message in his results. The correlation appears only when their records are later compared. This is the essential difference between entanglement and ordinary correlation: the relation is physically real, but it is not locally readable as a controllable signal.

This distinction is the entrance to the modern problem of quantum reality. Entanglement shows that nature is not assembled from independent local facts in the way classical intuition expects. Yet it also refuses to become a simple mechanism for superluminal influence. It occupies a strange middle ground: stronger than classical correlation, weaker than communication, and perhaps foundational enough to underwrite geometry itself.

1.3 Why the communication question matters

The communication question matters because it determines whether entanglement threatens the causal structure of physics. If entanglement allowed Alice to send Bob a chosen message instantaneously, then relativity would be violated in a direct operational sense. Different inertial observers could disagree about the temporal order of spacelike-separated messages, opening the door to causal paradoxes. Faster-than-light signaling would not merely be a technical extension of communication technology; it would destabilize the basic organization of cause and effect.

The Non-Communication Theorem prevents this. It says that no local action performed by Alice on her share of an entangled system can change the statistics available to Bob through measurements on his share alone. Bob's outcomes may be correlated with Alice's outcomes, but he cannot know which correlation pattern applies until Alice sends ordinary classical information. Entanglement gives correlation without unilateral control. It allows nature to violate classical separability without permitting usable superluminal messaging.

This point is especially important for ER=EPR and It from Qubit. If an entangled pair is interpreted geometrically as a kind of bridge, that bridge cannot be an ordinary traversable communication channel. A non-traversable Einstein-Rosen bridge is compatible with the Non-Communication Theorem because no message can pass through it. A traversable-wormhole-like protocol, in contrast, requires additional operations, couplings, or classical information. It is not free communication through entanglement alone.

Thus the communication question is not a side issue. It is the boundary condition for the whole field. Any proposed theory connecting entanglement, spacetime, wormholes, holography, or quantum computation must preserve the no-signaling structure of quantum mechanics. If it fails this test, it is not merely speculative; it is in conflict with one of the most secure operational features of quantum theory.

1.4 The working distinction: correlation, causation, and signaling

This paper uses a three-part distinction: correlation, causation, and signaling. Correlation means that two sets of outcomes display a structured statistical relationship. Causation means that one event physically contributes to the production of another event. Signaling means that one party can choose among alternatives in a way that changes what another party can locally observe.

Entanglement clearly produces correlation. Bell experiments demonstrate that these correlations are stronger than any local classical explanation allows. Whether one wants to describe the correlations as involving causation depends partly on interpretation. Collapse interpretations may speak as if Alice's measurement instantaneously affects Bob's state. Many-worlds interpretations avoid a single collapse event. Relational or informational interpretations shift attention to what can be known or operationally reconstructed. But across these interpretations, the signaling fact remains stable: Alice cannot use her local choices to send Bob a controllable message through entanglement alone.

This distinction also clarifies the meaning of apparent instantaneous collapse. If Alice and Bob share an entangled pair, Alice's measurement may allow her to update the joint description of the system immediately. But Bob's local experience does not change into a readable message. His measurement statistics remain the same. The update is real in the predictive structure of the joint quantum state, but it is not a signal traveling from Alice to Bob.

This framework is equally useful for attosecond studies of entanglement formation. A measured delay in the formation or emission dynamics of an entangled electron-ion system concerns the local temporal structure by which entanglement develops. It does not imply that established EPR correlations propagate across distance with that delay. Formation time is not communication time. A local quantum process may have resolvable temporal structure while nonlocal correlations still remain unusable for signaling.

The same distinction governs quantum teleportation. Teleportation uses entanglement, but it also requires classical information. Alice's measurement alone does not give Bob a usable reconstructed state. Bob must receive ordinary bits telling him which correction to apply. Teleportation therefore does not violate the Non-Communication Theorem; it dramatizes it.

1.5 Thesis of the paper

The thesis of this paper is that entanglement is physically real, experimentally demonstrable, and possibly foundational for spacetime geometry, but it remains bounded by non-communication. EPR identified the crisis. Bell experiments confirmed that the crisis is not merely philosophical. The Non-Communication Theorem preserved causal order by showing that nonclassical correlation cannot be converted into faster-than-light signaling. Quantum teleportation made this operational: entanglement is powerful, but it requires classical communication to become useful transmission.

ER=EPR and It from Qubit now place this structure in a wider setting. If entanglement is related to geometry, then spacetime may emerge from quantum informational relations rather than serving as the primitive container in which those relations occur. Holography, quantum error correction, SYK-like models, and traversable-wormhole-inspired protocols all point toward a picture in which geometry is encoded, reconstructed, and dynamically expressed through entangled quantum degrees of freedom.

Quantum computers may become the decisive experimental workbench for this possibility. They can physically instantiate entangled many-body systems, implement controlled Hamiltonians, test scrambling, probe teleportation dynamics, and explore whether holographic behavior survives scaling beyond toy models. However, quantum computers do not automatically make simulated spacetime into literal spacetime. The claim of quantum instantiation must be earned through robust observables, error-correcting structure, area-like entanglement behavior, chaos, scalability, and compatibility with no-signaling.

The paper therefore advances a restrained but ambitious position: entanglement may be the substrate from which geometry emerges, and quantum computers may provide the first controlled laboratories for studying that emergence. But any successful account must obey the Non-Communication Theorem. Entanglement may build connection, geometry, and perhaps spacetime itself; it cannot build a forbidden message.

2. EPR: The 1935 Origin of the Nonlocality Problem

2.1 The Einstein-Podolsky-Rosen argument

The EPR argument began as a challenge to the completeness of quantum mechanics. Einstein, Podolsky, and Rosen did not deny that quantum mechanics gave correct statistical predictions. Their deeper objection was that the theory seemed unable to provide a complete description of physical reality. If a system possessed a definite property, and if that property could be predicted with certainty without disturbing the system, then EPR argued that the property

should correspond to an element of reality. Quantum mechanics, however, appeared to deny simultaneous definite reality to certain pairs of properties, such as position and momentum, or later spin components along different axes.

The structure of the argument was subtle. EPR considered two systems that interacted and then separated. After separation, a measurement on one system could allow a prediction about the corresponding property of the other system. If the two systems were far apart, then measuring the first should not physically disturb the second, assuming locality. Yet quantum mechanics allowed different choices of measurement on the first system to determine which property of the second could be predicted. This created an apparent dilemma: either the distant system already possessed the relevant properties before measurement, in which case quantum mechanics was incomplete, or the measurement on the first system somehow affected the second system instantaneously, in tension with locality.

EPR chose the first horn of the dilemma. They argued that quantum mechanics must be incomplete because it failed to represent all elements of reality. Their paper was not originally a proof that nature is nonlocal. It was an argument that quantum mechanics, if taken as complete, seemed to require unacceptable nonlocality. The intended conclusion was that a deeper theory should restore locality and realism by supplying additional variables or a more complete description.

In retrospect, EPR identified the fault line on which twentieth-century physics would split. The question was not merely whether quantum mechanics was strange. The question was whether the world could still be understood as a collection of locally existing systems with definite properties, or whether the quantum state of a composite system had a reality that exceeded the independent reality of its parts.

2.2 Completeness, locality, and elements of reality

The EPR paper turned on three connected ideas: completeness, locality, and elements of reality. Completeness meant that every physically real property of a system should be represented in the theory. Locality meant that an action performed here should not instantly change the real physical state of a distant system there. An element of reality was defined operationally: if the value of a physical quantity can be predicted with certainty without disturbing the system, then there exists an element of physical reality corresponding to that quantity.

This definition was powerful because it avoided vague metaphysics. EPR did not simply assert that objects must have hidden properties. They argued that perfect predictability, combined with non-disturbance, justified assigning reality to the predicted quantity. If Alice can measure her subsystem and thereby predict Bob’s corresponding result with certainty, and if Alice’s

measurement cannot disturb Bob's distant subsystem, then Bob's subsystem must already possess the relevant property.

The difficulty arises because Alice may choose which property to measure. In the original EPR formulation, this involved position and momentum. In later spin-based versions, Alice may choose between different spin axes. Depending on her choice, quantum mechanics allows her to predict different corresponding properties of Bob's system. If locality is maintained, Bob's distant system cannot acquire one or another property merely because of Alice's free choice. Therefore, EPR concluded, Bob's system must already possess the relevant properties, even if quantum mechanics does not represent them simultaneously.

This is the completeness challenge. Quantum mechanics appeared to describe the joint system through a wavefunction that gave correct probabilities, but not a full inventory of local realities. From the EPR point of view, the wavefunction was therefore not the final word. It was either incomplete, or it required a kind of distant influence incompatible with relativistic causality.

The later development of Bell's theorem transformed this argument. EPR had hoped that locality and realism could be preserved by a deeper completion of quantum mechanics. Bell showed that any such local completion would satisfy statistical inequalities that quantum mechanics can violate. Experiments then showed that nature follows the quantum pattern. Thus EPR's dilemma did not disappear; it became sharper. The world does not seem to permit a simple return to local classical realism.

2.3 Einstein's objection to "spooky action at a distance"

Einstein's phrase "spooky action at a distance" captures his discomfort with the idea that quantum measurement could produce an instantaneous physical effect across space. The concern was not superstition or conservatism. Einstein's objection arose from a coherent physical principle: real physical influences should not propagate faster than light. Relativity had replaced Newtonian instantaneous action with field-mediated causal structure. If quantum mechanics reintroduced instantaneous influence, then the conceptual victory of relativity seemed threatened.

Einstein was willing to accept that quantum mechanics worked as a predictive tool. What he resisted was the claim that the wavefunction was a complete description of an individual physical system. If the wavefunction collapsed instantaneously across distance, and if the wavefunction represented physical reality itself, then distant reality seemed to change immediately when a local measurement occurred. Einstein saw this as unacceptable.

A key distinction, later clarified by quantum information theory, is the difference between update and signal. In ordinary probability theory, learning something about one system can update one's knowledge about another without physically affecting it. The glove example is

simple: discovering a left-handed glove in one box updates knowledge that the other box contains the right-handed glove. No physical influence travels between boxes. But quantum entanglement is not merely classical ignorance. Bell experiments show that the correlations cannot be explained by pre-existing local values. Thus the quantum update is deeper than ordinary Bayesian bookkeeping, but still not a controllable signal.

This is why Einstein's objection remains important even though the modern conclusion differs from his preferred solution. Physics did not return to classical locality. Instead, it found a more delicate structure. Entanglement violates classical separability, but the Non-Communication Theorem prevents superluminal message transmission. The "spooky" feature is real as nonclassical correlation, but not real as a usable faster-than-light telegraph.

Einstein's discomfort therefore continues to guide the field. Any interpretation of quantum mechanics, any theory of quantum gravity, and any proposed relation between entanglement and geometry must answer the same question: how can nature allow nonclassical connection without destroying causal order?

2.4 The difference between instantaneous update and physical signal

The apparent instantaneousness of quantum collapse has often been misunderstood. When Alice measures one half of an entangled pair, the joint quantum description changes. If the pre-measurement state is written as:

|Phi+> = (|00> + |11>)/sqrt(2)

then Alice's measurement in the 0/1 basis yields either 0 or 1, and Bob's corresponding result will match when measured in the same basis. From the viewpoint of the joint description, the state has been projected into one correlated branch. This looks instantaneous if Alice and Bob are far apart.

However, Bob cannot see Alice's result by looking at his local outcomes alone. Before Alice communicates classically, Bob sees a random sequence. If Alice measures, Bob's local statistics are random. If Alice does not measure, Bob's local statistics are still random. If Alice changes her measurement basis, Bob's local statistics remain random. The correlations are revealed only after Alice and Bob compare their records through an ordinary causal channel.

This is the operational heart of the Non-Communication Theorem. Alice's local action changes the joint description and the conditional correlations, but it does not change Bob's reduced local state in a way he can detect. In compact form, Bob's local state remains:

rho_B = I/2

The symbol I/2 means that Bob's subsystem is maximally mixed. It contains no readable message about Alice's choice. The joint state encodes correlation; the local state does not encode a signal.

This distinction resolves much of the apparent paradox without making entanglement classical. Quantum mechanics permits a kind of relational immediacy: once Alice has an outcome, she can correctly predict what Bob will find in a corresponding measurement. But quantum mechanics forbids unilateral communication: Alice cannot choose a message and imprint it onto Bob's local statistics through entanglement alone.

The difference between update and signal is also central to ER=EPR. If an entangled pair is interpreted as connected by a non-traversable bridge, that bridge may represent correlation or geometric connectedness, but it cannot function as a communication channel. A bridge that cannot transmit a signal is not a violation of relativity. In this sense, the Non-Communication Theorem is not an incidental technicality; it is what allows entanglement and relativistic causality to coexist.

2.5 EPR as the seed of the modern entanglement problem

EPR seeded almost every major development discussed in this paper. Bell's theorem grew directly from the EPR challenge by asking whether any local hidden-variable theory could reproduce quantum predictions. Experimental Bell tests then showed that the answer is no. Quantum teleportation used EPR-type entanglement as a resource, while demonstrating that classical communication remains necessary. The Non-Communication Theorem formalized why entanglement cannot become a faster-than-light signal. ER=EPR returned to the two 1935 Einstein papers and proposed that entanglement and geometric bridges may be two faces of one deeper structure. It from Qubit generalized this possibility into a research program in which spacetime itself may emerge from quantum information.

The original EPR paper did not use the modern language of qubits, quantum information, holography, or error-correcting codes. Yet the essential problem was already present. What is the physical meaning of a joint quantum state that cannot be decomposed into independent local realities? How can distant systems exhibit correlations stronger than classical locality permits? Why can those correlations not be used for communication? And what does this imply about the status of space as the background arena of physics?

The most radical possibility is that EPR did not merely expose a defect in quantum theory or an oddity of measurement. It may have exposed the fact that locality itself is emergent. If spacetime is built from entanglement, then the EPR puzzle is not a marginal paradox but a clue to the architecture of reality. The apparent conflict between quantum nonlocality and

relativistic causality may indicate that both quantum mechanics and spacetime geometry are surface expressions of a deeper informational order.

This is why EPR remains foundational. It marks the point at which physics was forced to distinguish separability from locality, correlation from signaling, and measurement update from causal influence. The rest of the paper follows that path forward: from EPR to Bell, from Bell to the Non-Communication Theorem, from teleportation to ER=EPR, and from It from Qubit to the possibility that quantum computers may instantiate the informational structures from which spacetime-like geometry emerges.

3. Bell Tests and the Direct Experimental Reality of Entanglement

3.1 Bell's theorem and the failure of local hidden variables

Bell's theorem transformed the EPR problem from a philosophical dispute into an experimentally testable question. EPR had argued that quantum mechanics must be incomplete if locality were to be preserved. Their hope was that a deeper theory could restore a world of local systems carrying definite properties, even if quantum mechanics itself did not describe those properties. Bell showed that this hope was not merely difficult; it was mathematically constrained. Any theory that preserves local hidden variables must obey certain statistical limits. Quantum mechanics predicts violations of those limits. Nature, by experiment, follows the quantum predictions.

The power of Bell's theorem is that it does not require knowing the details of the hidden variables. It applies to a broad class of theories in which measurement outcomes are determined by local properties carried by the particles and where Alice's choice of measurement setting cannot influence Bob's distant outcome faster than light. If such a local hidden-variable model were correct, then the correlations between Alice's and Bob's measurements would have to satisfy Bell inequalities.

Quantum mechanics predicts that entangled systems can violate these inequalities. This means that the observed correlations cannot be explained by particles simply carrying pre-written instructions from a common source. Something about the joint quantum state exceeds the logic of ordinary local separability.

This does not mean that Bell tests prove faster-than-light communication. They do not. Bell tests show that local classical realism fails. The Non-Communication Theorem still prevents Alice from using entanglement alone to send a message to Bob. Thus Bell's theorem divides two concepts that classical intuition often merges: locality as local hidden causation, and causality as no controllable superluminal signaling.

The result is a new kind of realism. Entanglement is real because it has measurable consequences that defeat local hidden-variable explanation. But it is not real in the manner of a mechanical signal traveling through space. It is a reality of joint quantum structure, not a classical influence moving from one object to another.

3.2 The CHSH inequality: S <= 2

The CHSH inequality is one of the clearest and most experimentally useful forms of Bell's theorem. It involves two observers, Alice and Bob, each of whom can choose between two measurement settings. Alice may choose setting A or A'. Bob may choose setting B or B'. Each measurement produces one of two possible outcomes, often represented as +1 or -1.

The central quantity is a combination of correlations:

$$S = E(A,B) + E(A,B') + E(A',B) - E(A',B')$$

Here E(A,B) is the average product of Alice's and Bob's outcomes when Alice uses setting A and Bob uses setting B. If their outcomes tend to match, E is positive. If they tend to differ, E is negative. If they are uncorrelated, E is near zero.

For any local hidden-variable theory, the CHSH value obeys:

$$|S| \leq 2$$

This bound is not a technological limit. It is a logical consequence of assuming that the particles carry local instructions and that Alice's setting cannot influence Bob's outcome, and Bob's setting cannot influence Alice's outcome, at spacelike separation. Under those assumptions, the correlations cannot exceed the classical limit.

The elegance of the CHSH form is that it converts a deep metaphysical issue into a measurable number. If experiments consistently find $|S| \leq 2$, then local hidden-variable models remain viable. If experiments find $|S| > 2$ under properly controlled conditions, then local hidden-variable models fail.

Quantum mechanics predicts precisely such a violation for entangled states. The experimental task is therefore to prepare entangled systems, choose measurement settings independently, collect outcome statistics, compute S, and determine whether the result exceeds the classical bound.

The CHSH inequality is important for this paper because it marks the first major bridge between the EPR problem and operational science. It gives a concrete test for whether entanglement is merely a strange mathematical description or a physically real departure from local classical explanation. Bell tests answer that question in favor of physical reality.

3.3 Quantum violation: S up to 2*sqrt(2)

Quantum mechanics does not merely violate the CHSH inequality slightly. For appropriately chosen measurements on a maximally entangled pair, quantum theory allows:

|S| <= 2*sqrt(2)

The value 2*sqrt(2), approximately 2.828, is known as the Tsirelson bound. It is greater than the classical local limit of 2, but still less than the algebraic maximum of 4. This fact is conceptually important. Quantum mechanics is more strongly correlated than local classical physics, but it is not arbitrarily nonlocal. It has its own internal limit.

This intermediate status is one of the deepest clues in the foundations of physics. If nature allowed |S| = 4 while still preserving no-signaling, then correlations could be even stronger than quantum mechanics permits. Such hypothetical correlations are sometimes used in theoretical studies to show that no-signaling alone does not uniquely determine quantum mechanics. Quantum theory occupies a special middle ground: stronger than classical locality, weaker than all logically possible no-signaling correlations.

The quantum violation arises from the structure of the entangled state and the noncommuting nature of measurement choices. For a Bell pair such as:

|Phi+> = (|00> + |11>)/sqrt(2)

Alice and Bob can choose measurement axes such that no pre-existing assignment of definite outcomes can reproduce all observed correlations. If one tries to imagine hidden instruction cards carried by the particles, the cards fail. They cannot satisfy every measurement context simultaneously.

This is not because information travels from Alice to Bob in the ordinary sense. Bob's local results remain individually random. Alice's local results also remain individually random. The violation appears only in the joint statistics after the two observers compare their records. This is why Bell violation and the Non-Communication Theorem are not enemies. Bell violation shows that the joint state is nonclassical. NCT shows that neither observer can locally read the joint structure as a message.

Thus the quantum value 2*sqrt(2) is not only a number. It is a signature of a new physical regime: one in which reality is not locally classical, but communication remains causally constrained.

3.4 Loophole-free Bell tests

Early Bell tests strongly supported quantum mechanics, but skeptics could point to experimental loopholes. Two major loopholes were especially important: the locality loophole and the

detection loophole. The locality loophole asks whether Alice's and Bob's measurement events were sufficiently separated that no ordinary light-speed or slower signal could connect them during the experiment. The detection loophole asks whether enough particles were detected to ensure that the observed sample fairly represented the whole ensemble.

A loophole-free Bell test is designed to close these and related escape routes simultaneously. The measurement settings must be chosen rapidly and independently. The measurement events must be spacelike separated. The detectors must be efficient enough that undetected events cannot plausibly hide a local realist explanation. Statistical analysis must also be strong enough to rule out chance fluctuations.

Modern loophole-free Bell experiments have achieved this standard using systems such as entangled photons, trapped ions, and solid-state spin systems. These experiments do not merely repeat the original Bell idea. They test the EPR question under conditions designed to block the most serious classical evasions. The result is that the violation of Bell inequalities persists.

This gives entanglement a special status among the strange features of quantum theory. It is not merely inferred from a single kind of experiment or from the success of quantum mechanics as a whole. It has been subjected to direct tests targeted at the precise question of whether local hidden-variable explanations can survive. The answer is no.

For the purposes of this paper, loophole-free Bell tests establish the first firm pillar. Entanglement is not an optional interpretation. It is a physical phenomenon with experimentally confirmed nonclassical correlations. Any later claim about ER=EPR, It from Qubit, holography, or quantum computation must begin from this point. Entanglement exists.

At the same time, loophole-free Bell tests reinforce the second pillar. No Bell experiment has allowed faster-than-light communication. The outcomes remain locally random. The correlations are revealed only after ordinary causal comparison. Thus the same experiments that destroy local hidden-variable realism also leave the Non-Communication Theorem intact.

3.5 What Bell experiments prove and do not prove

Bell experiments prove that the world cannot be explained by local hidden-variable theories of the simple EPR kind. They show that entangled systems produce correlations stronger than any theory can produce if it assumes both locality and predetermined classical outcomes. This is a profound result. It means that the physical world is not built from separable local facts in the way classical realism imagined.

Bell experiments also prove that entanglement is operationally real. It is not a mathematical artifact with no measurable consequence. It produces experimentally observed violations of

classical bounds. It can be used as a resource in quantum information tasks. It underwrites technologies such as quantum cryptography, quantum teleportation, quantum networks, and quantum computation.

But Bell experiments do not prove that information travels faster than light. They do not show that Alice can send Bob a chosen message by selecting her measurement setting. They do not show that a particle carries a tiny communication device. They do not by themselves prove ER=EPR, holography, or emergent spacetime. They prove the reality of nonclassical correlation, not the full geometry of quantum gravity.

This distinction is essential. The path from Bell to ER=EPR is not automatic. Bell establishes the existence of entanglement as a real physical structure. ER=EPR proposes that, in certain contexts, such entanglement may have a dual description as geometric connection. It from Qubit proposes that spacetime itself may arise from organized quantum informational relations. Quantum computers may instantiate some of those relations in controllable systems. But Bell experiments alone do not prove the whole chain.

What Bell experiments do provide is the indispensable foundation. They show that classical local separability is false. Once that is accepted, it becomes reasonable to ask whether spacetime locality itself is emergent rather than fundamental. If the most basic quantum correlations are not captured by local classical objects in a pre-existing space, perhaps the space in which objects appear separated is not the deepest level of description.

Bell tests therefore occupy a critical position in the paper's argument. They are the point where entanglement leaves philosophy and becomes experimentally enforced physics. They establish the reality of the quantum relation, while the Non-Communication Theorem establishes its causal boundary. From that foundation, the later questions become meaningful: can entanglement be geometrized, can geometry be encoded, and can a quantum computer physically instantiate the qubit structure from which an "It" emerges?

4. The Non-Communication Theorem as the Causal Boundary

4.1 Statement of the theorem

The Non-Communication Theorem is the principle that entanglement alone cannot be used to transmit a controllable message. It does not deny the reality of entanglement. It does not deny Bell inequality violations. It does not deny that measurements on entangled systems reveal correlations stronger than classical local physics allows. Its claim is more precise: no operation performed locally by Alice on her part of an entangled system can produce a detectable change in Bob's local measurement statistics unless ordinary classical information is also sent.

This theorem is the causal boundary separating quantum nonlocal correlation from faster-than-light communication. Without it, entanglement would become a superluminal telegraph. Alice could encode a message by choosing what measurement to perform, or whether to measure at all, and Bob could read that message instantly from his own local outcomes. Quantum theory forbids this. Bob's local outcomes remain random in exactly the right way. The joint statistics may be profoundly nonclassical, but the local statistics contain no chosen message.

The theorem can be stated in operational terms. Suppose Alice and Bob share an entangled state. Alice may measure her subsystem, rotate it, discard it, couple it to a device, or perform any allowed local quantum operation. Bob, having access only to his subsystem, cannot determine which operation Alice chose by examining his local data alone. Only after Alice sends him classical information can the relevant correlations be sorted and interpreted.

This is why quantum mechanics can violate Bell inequalities without violating relativistic causality. Bell tests show that nature is not locally classical. The Non-Communication Theorem shows that this nonclassicality cannot be weaponized into a forbidden signal. The two facts are not contradictory. Together they define the distinctive structure of quantum reality: stronger-than-classical correlation without faster-than-light communication.

The theorem is especially important for ER=EPR and It from Qubit. If entanglement has a geometric interpretation, that geometry cannot automatically become a traversable channel. A bridge may represent correlation, encoding, or emergent connectivity, but unless additional interactions or classical communication are supplied, it cannot transmit a message. Thus NCT is not a technical afterthought. It is the condition that any entanglement-based account of spacetime must obey.

4.2 Reduced density matrices and local randomness

The mathematical core of the Non-Communication Theorem is the reduced density matrix. A composite quantum system may have a joint state that contains strong correlations, while each local subsystem by itself appears random. The reduced density matrix captures what one observer can know or measure locally when the other part of the system is inaccessible.

For a simple Bell pair:

|Phi+> = (|00> + |11>)/sqrt(2)

the joint state is highly ordered. If Alice and Bob both measure in the 0/1 basis, their outcomes match. If Alice obtains 0, Bob obtains 0. If Alice obtains 1, Bob obtains 1. The whole state is not random in the ordinary sense. It has perfect correlation.

Yet Bob's local state alone is:

rho_B = I/2

This means Bob sees a maximally mixed state. His outcomes are locally random. If he measures in the 0/1 basis, he gets 0 half the time and 1 half the time. If he measures many particles from many shared Bell pairs, he sees a random sequence. There is no visible mark showing whether Alice measured, which basis she used, or what result she obtained.

The reduced density matrix is therefore a formal expression of a deep physical fact: entanglement is stored in the joint structure, not in either local part by itself. The information is relational. It appears when Alice and Bob compare records, not when either observer looks alone.

This also explains why entanglement is so difficult to describe using classical object language. In a classical correlated system, one might imagine that each particle carries hidden values. In an entangled system, the local part may not possess a definite value prior to measurement, while the joint system still has a definite relational structure. The whole has a state; the parts have mixed local descriptions.

The Non-Communication Theorem depends on this local mixedness. Alice may change the conditional description of Bob's system from her point of view, but she cannot change Bob's reduced density matrix in a way that Bob can observe without her classical message. The local randomness is not an accident or a limitation of Bob's equipment. It is built into the structure of the quantum state.

4.3 Alice cannot signal by choosing a measurement basis

A common misunderstanding is that Alice should be able to signal by choosing which basis to measure. For example, Alice and Bob may share many copies of the Bell state:

|Phi+> = (|00> + |11>)/sqrt(2)

Alice might try to send a 0 by measuring in the 0/1 basis and a 1 by measuring in the +/− basis. Since Bob's particle is entangled with Alice's, it may seem that Bob should be able to detect Alice's choice by measuring his particles. If this worked, entanglement would allow faster-than-light communication.

It does not work. If Alice measures in the 0/1 basis, Bob's conditional state becomes either |0> or |1>, depending on Alice's result. But Bob does not know which result Alice obtained. Averaging over Alice's possible outcomes, Bob's local state remains:

rho_B = I/2

If Alice measures in the +/− basis, Bob's conditional state becomes either |+> or |->, depending on Alice's result. Again, Bob does not know which result Alice obtained. Averaging over those possible outcomes, Bob's local state remains:

rho_B = I/2

Thus Bob cannot distinguish Alice's basis choice by examining his subsystem alone. The ensemble he sees is locally identical in both cases. The decomposition of the mixed state changes, but the mixed state itself does not. Alice may know how Bob's particles are conditionally organized relative to her outcomes, but Bob cannot access that conditional organization until Alice sends him classical information.

This point is subtle. The same density matrix can be decomposed into different ensembles. For example:

I/2 = (1/2)|0><0| + (1/2)|1><1|

and also:

I/2 = (1/2)|+><+| + (1/2)|-><-|

These are different descriptions of the same local mixed state. Alice's measurement basis can determine which ensemble decomposition is relevant, but Bob cannot tell which decomposition applies from local measurements alone. Every possible local test gives the same statistics.

This is one of the strongest expressions of NCT. Alice has real choices. Her measurement basis matters to the joint correlations. But her choices do not become locally visible to Bob. Entanglement can coordinate outcomes after comparison; it cannot transmit the comparison itself.

4.4 Bob's local state remains unchanged

The phrase "Bob's local state remains unchanged" must be understood carefully. It does not mean that nothing happens in the joint quantum description. It means that the state available to Bob through local measurements alone is invariant under Alice's local operations when averaged over outcomes. Bob's accessible statistics do not change.

Suppose Alice performs a measurement but does not reveal the outcome. From the perspective of the full joint state, the system may undergo projection or become entangled with Alice's measuring apparatus. From Alice's perspective, after she obtains a result, she can assign a conditional state to Bob's subsystem. But from Bob's perspective, before receiving any classical information, his reduced state is still the same mixed state.

This is why the word “collapse” can mislead. If collapse is imagined as a physical shock wave traveling instantly across space, it seems to threaten relativity. If collapse is understood as an update of the conditional joint description relative to a measurement outcome, then the absence of signaling becomes intelligible. Bob does not locally experience a readable change.

The general structure can be described as follows. The joint state rho_AB contains correlations between Alice and Bob. Bob’s local state is obtained by ignoring Alice’s subsystem:

rho_B = Tr_A(rho_AB)

Here Tr_A means taking the partial trace over Alice’s degrees of freedom. Alice’s local operation may change the joint bookkeeping, but if Bob has no access to Alice’s result, his reduced state remains operationally the same for signaling purposes.

This is not merely a mathematical convenience. It corresponds directly to what Bob can measure. Any observable Bob chooses has expectation values determined by rho_B. If rho_B is unchanged, all of Bob’s local measurement probabilities are unchanged. Therefore there is no signal.

This local invariance is the reason quantum theory can permit instantaneous-looking correlations while remaining compatible with relativistic causality. The joint state may be nonseparable. The conditional state may update. The correlations may violate Bell inequalities. But Bob’s locally measurable state does not carry Alice’s chosen message. NCT is the firewall between nonlocal correlation and causal paradox.

4.5 Why classical comparison is required

Classical comparison is required because entanglement correlations are relational. Neither Alice’s data alone nor Bob’s data alone contains the full structure. Each observer sees randomness locally. The nonclassical order appears only when their records are brought together.

Imagine Alice and Bob perform measurements on a long sequence of shared entangled pairs. Alice records her settings and outcomes. Bob records his settings and outcomes. Alice’s list by itself looks random. Bob’s list by itself looks random. Only when the two lists are compared can they compute correlations such as:

E(A,B)

or the CHSH combination:

S = E(A,B) + E(A,B') + E(A',B) - E(A',B')

Without comparison, there is no observed Bell violation. The violation exists in the joint statistics, not in either local record. This is why a classical communication channel is necessary. Alice and Bob must exchange information about settings, outcomes, timing, and trial pairing in order to reveal the pattern.

The same rule governs quantum teleportation. Alice's Bell measurement entangles her unknown input state with her half of a shared pair and projects Bob's subsystem into a related state. But Bob does not know which correction to apply. Alice must send classical bits. Only after receiving those bits can Bob reconstruct the teleported state. Entanglement supplies the nonclassical resource; classical communication supplies the usable instruction.

This is not a failure of quantum mechanics. It is the precise structure that protects causality. Entanglement allows correlations that no classical local model can explain, but it does not allow either party to access the correlation pattern unilaterally. The pattern is distributed across the joint system and the later comparison.

Classical comparison also clarifies ER=EPR. If entanglement corresponds to a bridge, the bridge is not automatically a communication tunnel. To send a message through a traversable-wormhole-like protocol, one needs additional allowed interactions or side information. The mere existence of entanglement does not suffice. Without the extra channel, the bridge remains non-traversable in the operational sense.

Thus classical comparison is not a mundane add-on. It is the act that converts hidden relational structure into publicly usable information. Entanglement by itself gives the structure. Communication gives access to the structure.

4.6 How NCT preserves relativity while allowing nonclassical correlation

The Non-Communication Theorem performs one of the most important reconciliations in modern physics. It allows quantum mechanics to be nonclassical without allowing operational violations of relativistic causality. This reconciliation is delicate. If quantum mechanics were fully classical and local, Bell violations would not occur. If quantum mechanics allowed controllable faster-than-light signaling, relativity would fail as a causal framework. NCT allows the middle position: nonclassical correlation without superluminal communication.

Relativity is fundamentally concerned with causal order. Events outside each other's light cones cannot be connected by controllable signals without generating frame-dependent causal contradictions. If Alice could send Bob an instantaneous message using entanglement, then some observers would describe Bob as receiving the message before Alice sent it. With suitable arrangements, causal loops could arise. NCT prevents this by ensuring that Bob's local data cannot encode Alice's chosen message.

At the same time, NCT does not restore classical separability. Bell tests still rule out local hidden-variable explanations. The world is not a collection of independent local facts in the classical sense. The joint quantum state remains physically meaningful. Entanglement remains a real resource. Quantum teleportation, quantum cryptography, and quantum computation all depend on this nonclassical structure.

This combination is why entanglement is so relevant to quantum gravity. If spacetime locality is not fundamental, but emerges from entanglement, then NCT may be one of the principles that governs how emergent causal structure remains stable. The theorem may be more than a rule about laboratory measurements. It may be a clue to how quantum informational reality produces a world with light cones, causal order, and no usable superluminal channels.

In ER=EPR terms, NCT explains why entanglement can be geometrically suggestive without becoming a forbidden shortcut. A non-traversable bridge represents connectedness without signaling. A traversable protocol requires additional causal ingredients. The theorem therefore draws the boundary between permissible emergent geometry and impossible communication.

The final lesson is that entanglement changes the meaning of separation, but not the operational prohibition on faster-than-light messages. Two systems may be deeply related even when far apart. Their joint state may defy classical explanation. Their correlations may reveal a hidden order that points toward holography or emergent spacetime. But no observer can use those correlations alone to send a chosen message outside the light cone. This is the causal boundary that any future theory of It from Qubit must respect.

5. Quantum Teleportation: Entanglement Plus Classical Information

5.1 Why teleportation is not faster-than-light travel

Quantum teleportation is often misunderstood because its name suggests science-fiction transport. In actual quantum physics, teleportation does not move matter, does not send usable information instantaneously, and does not allow a person, particle, or message to bypass ordinary causal structure. It is a protocol for transferring an unknown quantum state from one system to another using shared entanglement and classical communication. The state is reconstructed at the receiving end only after the receiver obtains ordinary classical information from the sender.

This distinction is essential. Teleportation uses entanglement, but it does not use entanglement alone. Alice and Bob first share an entangled pair. Alice also possesses a third system whose unknown quantum state is to be transferred. She performs a joint measurement on the unknown state and her half of the entangled pair. This measurement destroys the original local

copy of the unknown state, preventing cloning. Bob's distant system is then left in a state related to the original, but not yet in the correct usable form. To complete the protocol, Alice must send Bob classical bits describing her measurement outcome. Only then can Bob apply the appropriate correction and recover the original state.

Thus the protocol respects the Non-Communication Theorem. Before Bob receives Alice's classical message, his local state is not a readable transmission of the unknown state. It is effectively scrambled from his point of view. He cannot determine what Alice teleported, whether Alice completed the measurement, or which correction is needed. The entanglement supplies a nonclassical resource, but the classical message supplies the operational instruction.

Teleportation therefore dramatizes the boundary between correlation and communication. Entanglement creates the possibility of transferring a quantum state without directly carrying that state through space as a physical object. But the usable completion of the transfer remains limited by classical causal communication. In this sense, teleportation is one of the clearest demonstrations that quantum mechanics is both stranger and more disciplined than popular descriptions suggest. It is not faster-than-light travel. It is an entanglement-assisted state-transfer protocol constrained by ordinary communication.

5.2 The role of shared entanglement

Shared entanglement is the indispensable resource in teleportation. Without it, Alice could not transfer an unknown quantum state to Bob using only a small amount of classical information. The entangled pair functions as a pre-established relational structure between Alice's laboratory and Bob's laboratory. It is not a message, but it is a channel resource that can be activated when combined with Alice's measurement and subsequent classical communication.

A simple version begins with Alice and Bob sharing a Bell pair:

|Phi+> = (|00> + |11>)/sqrt(2)

Alice holds one qubit from this pair, and Bob holds the other. Alice also holds a separate qubit in an unknown state:

|psi> = a|0> + b|1>

The goal is to transfer |psi> to Bob without Alice knowing the values of a and b. This is crucial. If Alice knew the state, she could simply describe how to prepare it. Teleportation is powerful because it transfers a state that may be unknown even to the sender.

The shared Bell pair does not itself contain the unknown state. Before Alice's measurement, Bob's local qubit remains maximally mixed. He cannot extract |psi> from it. The entangled pair instead provides the relational capacity needed for the later protocol. It is like a pre-positioned

quantum bridge whose structure is inactive until Alice performs the correct joint measurement and sends the classical result.

This role of entanglement is deeply relevant to ER=EPR and It from Qubit. Entanglement is not merely a decorative correlation; it is an operational resource. It can enable tasks impossible in classical information theory. Yet its power is not identical to ordinary communication. The resource is real, but incomplete by itself. It must be paired with allowed operations and classical messages to produce usable effects.

The shared entangled state is therefore the silent infrastructure of teleportation. It links Alice and Bob in a way no classical shared randomness can duplicate, but it remains non-signaling until embedded in the full protocol.

5.3 The role of Alice's classical bits

Alice's classical bits are the reason teleportation does not violate causality. After Alice performs her joint Bell measurement, she obtains one of four possible outcomes. These outcomes can be labeled with two classical bits: 00, 01, 10, or 11. Each outcome tells Bob which correction he must apply to recover the original state.

Without these bits, Bob's qubit is not useful as the teleported state. It is one of four related versions of the original state, but Bob does not know which one. From his local point of view, the ensemble remains unreadable. The unknown state has not become available to him in operational form.

The structure can be summarized as follows. Alice's unknown state is:

$|\psi\rangle = a|0\rangle + b|1\rangle$

After Alice's Bell measurement, Bob's qubit is conditionally one of the following possibilities:

$|\psi\rangle$

$X|\psi\rangle$

$Z|\psi\rangle$

$XZ|\psi\rangle$

Here X and Z represent standard quantum correction operations. Alice's two classical bits tell Bob whether to apply no correction, X, Z, or XZ. Until Bob receives those bits, he cannot know which state he has. He cannot extract the coefficients a and b. He cannot use the qubit as the intended teleported state.

This is why teleportation is not instantaneous transmission. Alice's measurement may establish a conditional relation between the unknown input and Bob's system, but the relation is not locally accessible to Bob. The classical message is necessary to unlock the result. Since that message cannot travel faster than light, the completed teleportation cannot occur faster than light in any usable sense.

The classical bits also reveal a deeper lesson: quantum information and classical information are not interchangeable. Entanglement can perform part of a task that classical communication alone cannot accomplish efficiently, but classical information is still required to coordinate the branches of the quantum process. Teleportation works because it combines two different resources. It is not pure quantum magic. It is a precisely structured hybrid of entanglement, measurement, and classical communication.

5.4 Bob's correction operation

Bob's correction operation is the final step that turns potential teleportation into completed teleportation. Before correction, Bob's qubit is related to Alice's original state, but generally not identical to it. After Alice sends the two classical bits, Bob performs the corresponding local operation and obtains the original unknown state.

If Alice's outcome is 00, Bob may need to do nothing:

|psi> -> |psi>

If Alice's outcome is 01, Bob applies X:

X|psi> -> |psi>

If Alice's outcome is 10, Bob applies Z:

Z|psi> -> |psi>

If Alice's outcome is 11, Bob applies XZ or the equivalent inverse correction:

XZ|psi> -> |psi>

The exact labeling depends on the convention used for the Bell measurement, but the principle is stable. Alice's result identifies the transformation separating Bob's conditional state from the intended state. Bob's local correction removes that transformation.

This step is important because it shows that teleportation is not passive reception. Bob does not simply look at his qubit and find the state waiting there in usable form. He must act, and he can act correctly only after receiving Alice's classical information. The protocol therefore has an irreducible causal structure. Alice's measurement, Alice's message, and Bob's correction form an ordered sequence.

Bob's correction also illustrates the no-cloning structure of quantum mechanics. Alice's Bell measurement destroys the original local availability of |psi>. The state is not copied to Bob while remaining intact with Alice. Instead, the quantum information is transferred. This matters because unrestricted copying of unknown quantum states would itself create deep conflicts with quantum mechanics and could threaten no-signaling constraints. Teleportation avoids this by preserving the no-cloning theorem.

In the context of emergent spacetime, Bob's correction has a useful interpretation. Entanglement may provide a latent geometry-like linkage, and Alice's measurement may inject or redirect quantum information, but usable transmission still requires an authorized causal operation. A traversable-wormhole-like protocol has the same character. The apparent shortcut is not free. It depends on coupling, timing, and classical or causal control. The final reconstruction is not evidence against NCT; it is evidence for the precise way NCT structures all usable quantum communication.

5.5 Teleportation as an operational demonstration of NCT

Quantum teleportation is one of the best operational demonstrations of the Non-Communication Theorem because it appears at first glance to challenge the theorem, but on inspection obeys it exactly. The protocol uses entanglement to transfer a quantum state across distance, yet it cannot be completed without classical communication. This makes teleportation a living example of the rule that entanglement is powerful but non-signaling.

The apparent paradox is easy to state. Alice measures her system, and Bob's system becomes conditionally related to Alice's unknown input state. If this conditional relation is established immediately, why can Bob not receive the state immediately? The answer is that the conditional relation is not locally readable. Bob's local density matrix still contains no usable message. He cannot know which correction to apply. He cannot distinguish successful teleportation from other possible local mixtures without Alice's classical information.

This is the same structure seen in Bell tests. Alice and Bob may possess correlations that no local hidden-variable model can explain, but the correlations appear only when their records are compared. Each local record alone remains random. Teleportation adds an active protocol on top of that fact. It shows how entanglement can become useful only when embedded in a causally ordered procedure.

The lesson can be stated compactly:

Entanglement alone = correlation without message

Classical communication alone = message without unknown quantum state transfer

Entanglement + classical communication = teleportation

This combination is the operational heart of the field. Quantum information is not classical information wearing a strange costume. It has different rules, different resources, and different limitations. Entanglement can accomplish tasks that classical systems cannot, but it does not abolish causal order.

Teleportation also provides a bridge to ER=EPR. Traversable-wormhole protocols are closely related to quantum teleportation. A message appears to pass through a dual geometric channel, but the underlying quantum information process requires specific interactions that make the protocol causal and non-paradoxical. This means that a wormhole-like interpretation does not automatically imply forbidden signaling. The geometry, if real or emergent, is constrained by the same operational rules that govern teleportation.

For this paper, teleportation occupies a crucial middle position. EPR introduced the nonlocality problem. Bell confirmed the reality of nonclassical correlation. NCT defined the causal boundary. Teleportation shows how the boundary works in an active quantum information task. It proves that entanglement can be used, but not abused. It can transfer a quantum state, but not without a classical message. It can support an emergent geometry-like interpretation, but not a causality-violating channel. In this sense, teleportation is not an exception to non-communication. It is one of its clearest confirmations.

6. Attosecond Entanglement Formation: Time Structure Without Signaling

6.1 The 232 attosecond helium result

The reported 232 attosecond result belongs to a different category than the older EPR question of apparently instantaneous distant correlation. It does not show that entanglement travels across space at a finite speed, nor does it show that EPR correlations are delayed by 232 attoseconds. Rather, it concerns the ultrafast local dynamics by which entanglement can form during the photoionization of helium. In such an experiment, a photon interacts with a helium atom, one electron is emitted, and the remaining ion is left in a correlated quantum state. The departing electron and the residual bound electron are not independent products of a simple one-particle process. Their final states carry information about a coupled two-electron event.

An attosecond is 10^-18 seconds. This is the natural time domain of electron motion, photoemission, and ultrafast charge redistribution inside atoms and molecules. A time delay of approximately 232 attoseconds is unimaginably brief by human standards, but physically meaningful at the electronic scale. It is long enough to reveal that the formation of the final entangled electron-ion state is not adequately described as an instantaneous click with no internal structure. The escaping electron is better understood as a wave packet whose emission, phase, and correlation with the remaining system unfold over a measurable interval.

The key point is that this delay is a property of a local atomic process. It concerns how an entangled final state arises from a specific interaction inside helium. It is not a universal delay for entanglement itself. It is not a speed limit for quantum correlation. It is not a hidden signaling time. It is a dynamical formation time associated with a particular physical system, measurement protocol, and final-state channel.

This distinction is important because popular language can easily confuse “how fast entanglement forms” with “how fast entanglement communicates.” The first is a legitimate question about local quantum dynamics. The second, if interpreted as controllable signaling through entanglement alone, is forbidden by the Non-Communication Theorem.

6.2 Local formation of electron-ion entanglement

In helium photoionization, the atom begins as a two-electron quantum system. The electrons are not merely two independent beads orbiting a nucleus. Their motions are correlated by Coulomb interaction, antisymmetry, and the structure of the total quantum state. When a photon ionizes the atom, one electron is ejected while the other remains bound to the helium ion. The final state can contain entanglement between the outgoing electron and the residual ion.

This local formation process matters because it shows that entanglement is not only a static resource prepared in advance, as in many Bell-pair experiments. Entanglement can also be generated dynamically during an interaction. The atom, photon, escaping electron, and remaining ion form a quantum process in which correlations are created, redistributed, and finally recorded in measurable observables such as energy, phase, angular distribution, and time delay.

The departing electron may leave the atom in different ways depending on the final state of the ion. If the residual ion is left in one energy state, the outgoing electron wave packet may have one phase and effective emission time. If the residual ion is left in another energy state, the outgoing wave packet may have a slightly different phase and effective emission time. These alternatives are not merely classical labels. They can be coherently related. The final quantum description may require a superposition of channels whose relative phase carries information about the entanglement between the emitted and bound parts of the system.

This is why attosecond timing can probe entanglement formation. Time delay is not just a stopwatch reading. In quantum scattering and photoemission, time delay is often inferred from phase behavior. The phase of a wave packet as a function of energy contains information about when, in an operational sense, the particle appears to emerge from the interaction region. If the phase structure depends on the state of the remaining ion, then the time delay can reveal electron-electron coherence and entanglement.

The result is a more textured picture of quantum correlation. Entanglement is not always an abstract property assigned after preparation. In local atomic processes, it can be watched indirectly as it forms. But this does not weaken NCT. A locally generated entangled state still cannot be used by one party to send a chosen faster-than-light message to another party. The formation may have time structure; the later nonlocal correlation remains non-signaling.

6.3 Why this is not a distance-dependent EPR delay

The 232 attosecond result should not be interpreted as a distance-dependent EPR delay. In an EPR-type setup, two systems may be separated by large distances after entanglement has been prepared. Measurements on the separated systems reveal correlations that violate classical local expectations. But the Non-Communication Theorem says that neither party can use those correlations alone to send a message. Therefore, assigning a signal velocity to EPR correlation is already misleading. There is no controllable signal whose travel time can be measured.

A distance-dependent delay would mean something like this: Alice measures here, Bob's particle receives an effect there after a time proportional to the separation distance. That is not what the helium attosecond experiment studies. The helium system is local. The relevant delay occurs during the emission and correlation-building process inside or near the atom. It is associated with the atomic interaction region, not with two laboratories separated by kilometers.

If the electron later travels far away, the entanglement can persist across distance. But the measured 232 attosecond feature is not the time it takes for a message to cross that later separation. It is tied to the origin event: the photoionization dynamics that created the entangled outgoing electron-ion state. Once created, the entangled state may be spatially extended, but its existence does not supply a usable communication channel.

This distinction blocks a common misconception. One might imagine that early quantum theory believed entanglement was instantaneous, while modern attosecond physics has discovered that it actually takes 232 attoseconds to "arrive." That is not the correct historical or physical interpretation. The older instantaneous language concerned the apparent update of a joint quantum description after measurement. The attosecond result concerns the finite local dynamics by which a specific entangled state can be generated during electron emission.

Formation time and nonlocal measurement correlation are different categories. The first can be probed using ultrafast spectroscopy. The second is constrained by Bell experiments and NCT. A time-resolved entanglement-formation experiment enriches the physics of how entanglement arises, but it does not convert entanglement into a propagating signal. It also does not contradict the no-signaling structure that protects relativity.

6.4 Birth-time structure, wave packets, and interelectronic coherence

The phrase “birth time” in attosecond photoionization should be understood operationally rather than naively. An electron is not a tiny classical pellet sitting at a definite point until a photon knocks it out at a single sharply defined instant. The emitted electron is a quantum wave packet. Its apparent time of emergence is inferred from phase, energy, and interference information. Different components of the wave packet can carry different effective emission times.

In helium, the two-electron structure makes this richer. The outgoing electron is not born independently of the electron left behind. The residual ion can be left in different states, and the outgoing electron’s energy and phase depend on that final ionic state. If the alternatives remain coherent, the final state is not merely a classical mixture of possibilities. It is a quantum superposition involving both the outgoing electron and the residual ion.

A schematic way to write the situation is:

|final> = c1 |electron channel 1>|ion state 1> + c2 |electron channel 2>|ion state 2>

This expression says that the outgoing electron channel and the ion state are linked. The coefficients c1 and c2 carry amplitudes and phases. If the total state cannot be factored into a separate electron state times a separate ion state, then the electron and ion are entangled.

The measured time delay is connected to this coherent channel structure. The phase relation between the channels can reveal that the electron’s effective emission is not the same for each correlated final state. The observed delay is therefore an attosecond-scale signature of interelectronic coherence. It is a probe of how the two-electron quantum system reorganizes itself during ionization.

This makes the result important for foundational discussions, but in a careful way. It shows that entanglement can be dynamically generated and temporally structured at the smallest electronic timescales. It supports the view that entanglement is not merely an abstract bookkeeping device but a real physical feature of quantum processes. However, it does not support faster-than-light messaging. The local wave-packet dynamics create the correlated state; they do not create a controllable nonlocal communication channel.

For this paper, the lesson is that time enters entanglement in more than one way. There can be a time of preparation, a time of formation, a time of measurement, a time of classical comparison, and a time associated with local wave-packet emergence. Confusing these times leads to false paradoxes. Separating them clarifies how entanglement can be both dynamically real and non-signaling.

6.5 The distinction between formation time and communication time

The most important conceptual lesson of the attosecond result is the distinction between formation time and communication time. Formation time concerns how a quantum state comes into being through a physical process. Communication time concerns how a chosen message becomes available to a receiver. Entanglement can have a formation time without having a communication time in the signaling sense.

When a helium atom is photoionized, the final entangled state of the outgoing electron and residual ion is generated through real dynamics. Those dynamics involve interaction, phase evolution, electron-electron correlation, and wave-packet formation. It is therefore meaningful to ask how long this process takes, or whether different channels have different effective emission times. Attosecond physics gives experimental access to this question.

By contrast, when Alice and Bob share an entangled pair at a distance, Alice cannot choose a message and cause Bob's local statistics to change. There is no usable communication event produced by her measurement alone. Bob's local density matrix remains unchanged for signaling purposes. Therefore there is no communication time to measure. The correlation may be revealed later, but only after Alice and Bob compare records through a classical channel.

This distinction can be summarized as:

Formation time = time required for a physical process to generate an entangled state

Correlation revelation time = time at which separated records are compared

Communication time = time required for a chosen message to reach a receiver

Entanglement participates in the first two. Entanglement alone does not supply the third.

This framework also helps interpret quantum-computer wormhole experiments. A quantum processor may implement a circuit over a definite time. It may generate entanglement, scrambling, teleportation-like dynamics, and a dual geometric description. The circuit has a duration. The simulated or emergent process has an internal time structure. But none of this implies a violation of NCT. A traversable-wormhole-like protocol still requires allowed couplings and causal information. It is a structured quantum process, not a free superluminal channel.

The attosecond result therefore strengthens, rather than weakens, the paper's central thesis. Entanglement is not an instantaneous magical link detached from dynamics. It can be formed through measurable physical processes with ultrafast temporal structure. Yet once formed, its nonclassical correlations remain bounded by non-communication. Time-resolved entanglement formation reveals how quantum connection arises; the Non-Communication Theorem explains why that connection cannot be turned into a forbidden message.

7. ER=EPR: Entanglement as Geometric Connection

7.1 The 1935 pairing of EPR and Einstein-Rosen bridges

The phrase ER=EPR joins two ideas that were both born in 1935 but were not originally treated as a single theory. EPR refers to the Einstein-Podolsky-Rosen argument about quantum completeness, locality, and distant correlations. ER refers to the Einstein-Rosen bridge, a geometric structure appearing in general relativity as a connection between two regions of spacetime. The historical coincidence is striking: in the same year, Einstein was involved in one paper that exposed the nonlocal strangeness of quantum mechanics and another that explored bridge-like structures in spacetime geometry. ER=EPR later proposed that these two problems may not be separate.

The original EPR paper asked whether quantum mechanics could be complete if a measurement on one system seemed to determine the state of another distant system. The original Einstein-Rosen bridge paper explored a way of representing particles or spacetime structures without singularities by extending the geometric manifold. Neither paper claimed that quantum entanglement was literally a wormhole. The conceptual merger came much later, after black hole thermodynamics, quantum information theory, and holography had changed the language of theoretical physics.

The importance of the 1935 pairing is symbolic and structural. EPR identified a nonclassical relation between separated quantum systems. ER identified a geometric connection between separated spacetime regions. ER=EPR asks whether the quantum relation and the geometric connection are two descriptions of one underlying reality. If so, entanglement would not merely occur inside spacetime. Entanglement would participate in generating what spacetime connectivity means.

This does not mean that every entangled laboratory pair is a macroscopic tunnel through space. The claim is more subtle. In certain gravitational or holographic contexts, the same physics may be described either as entanglement in a quantum theory or as a bridge in a geometric theory. The phrase ER=EPR compresses this possibility into a memorable formula:

ER = EPR

Read carefully, this is not an ordinary equality between two visible objects. It is a proposed equivalence between two descriptions: geometric connection and quantum entanglement.

7.2 Maldacena and Susskind’s 2013 conjecture

Maldacena and Susskind’s 2013 proposal gave ER=EPR its modern form. Their conjecture arose partly from the black hole information problem and the firewall debate. If quantum mechanics is unitary, then black hole evaporation must preserve information. Yet the smoothness of the

black hole horizon, the monogamy of entanglement, and the structure of Hawking radiation appeared to create tension. ER=EPR offered a new way to think about the relation between entanglement and spacetime geometry.

The central image is that two entangled black holes may be connected by an Einstein-Rosen bridge. In the case of an eternal two-sided black hole in anti-de Sitter space, the two exterior regions can be described by two entangled boundary quantum systems. The thermofield double state provides a precise example:

|TFD> = sum_n exp(-beta*E_n/2) |n>_L |n>_R / sqrt(Z)

This expression represents two copies of a quantum system, labeled L and R, entangled in a special thermal pattern. In the holographic description, that entangled state corresponds to a two-sided black hole with a bridge between the two sides. The bridge is not traversable in the ordinary sense. It represents geometric connectedness without permitting a message to pass from one exterior region to the other.

ER=EPR generalized this lesson. If entanglement between two black holes can be represented as a bridge, perhaps entanglement more broadly has a geometric aspect. The conjecture suggested that quantum entanglement and spacetime connectivity are not independent phenomena. The geometry may be the large-scale, gravitational expression of an underlying entangled quantum state.

The conjecture is powerful because it transforms the EPR problem. Instead of asking how two distant particles coordinate their outcomes through pre-existing space, ER=EPR asks whether the apparent distance itself is secondary. The quantum state may define connectivity more fundamentally than classical geometry does. In this view, entanglement is not a mysterious influence crossing space. It is part of the structure from which spatial relation emerges.

However, ER=EPR remains a conjecture, not an experimentally established fact. Its strongest support comes from holographic models, black hole thought experiments, quantum information theory, and the consistency demands of quantum gravity. It is a theoretical organizing principle whose full physical scope remains open.

7.3 Entangled black holes and non-traversable bridges

The cleanest setting for ER=EPR is the entangled black hole. Imagine two black holes formed in an entangled state. In the ER=EPR picture, the entanglement between them may be described geometrically as an Einstein-Rosen bridge. The bridge is a connection in the extended geometry, but it is not a usable tunnel for travel or communication. This distinction is central.

A non-traversable bridge can connect two regions geometrically without allowing a signal to pass through. This is not a contradiction. In general relativity, the causal structure of a

spacetime determines which paths can be used by signals. A bridge may exist in the mathematical geometry while still pinching off too quickly, or being arranged in such a way, that no traveler or message can get from one side to the other. The connection is real in the geometric description, but not operationally traversable.

This mirrors the structure of entanglement. Entanglement connects two systems through a joint quantum state, but the Non-Communication Theorem prevents that connection from being used for direct signaling. Alice and Bob may share correlations stronger than any classical local explanation allows, but Alice cannot send Bob a chosen message merely by measuring her side. The bridge and the Bell pair share the same causal discipline: connection without communication.

The analogy can be stated as:

Entanglement = nonclassical correlation without signal

Non-traversable bridge = geometric connection without passage

ER=EPR proposes that these are not merely analogous. In some settings, they may be dual descriptions of the same underlying physical fact. The entanglement is the quantum description; the bridge is the gravitational description.

This helps explain why ER=EPR does not automatically produce science-fiction wormholes. If the bridge is non-traversable, then it cannot be used as a shortcut through spacetime. It does not let information escape the light cone. It does not permit causal paradox. It provides a geometric way to represent entanglement while preserving the Non-Communication Theorem.

The entangled black hole case is therefore more than an exotic example. It is the conceptual prototype. It shows how quantum information and geometry can be related without violating causality. It also suggests that spacetime connectedness may depend on the pattern and strength of entanglement. Reduce or rearrange the entanglement, and the geometry may stretch, disconnect, or change.

7.4 Why ER=EPR does not violate NCT

ER=EPR would be untenable if it implied that entanglement automatically permits faster-than-light communication. The Non-Communication Theorem is one of the strongest constraints on any serious version of the conjecture. Fortunately, the basic ER=EPR picture is naturally compatible with NCT because the bridges associated with ordinary entanglement are non-traversable.

In standard entanglement, Alice cannot signal to Bob by choosing a measurement basis. Bob's reduced state remains unchanged for signaling purposes:

rho_B = I/2

or, more generally:

rho_B = Tr_A(rho_AB)

Alice's local operation may change the conditional correlations in the joint description, but Bob's local observable statistics remain the same until classical information arrives. If ER=EPR gives this entanglement a geometric interpretation, the geometry must respect the same rule. The bridge may encode correlation, but it cannot transmit Alice's chosen message.

This is why the phrase "wormhole" must be handled carefully. In ordinary language, a wormhole suggests a tunnel through which something can pass. In ER=EPR, the relevant bridge is generally not a traversable transport channel. It is better understood as a geometric representation of a joint quantum state. The two sides are connected in the description, but the connection is causally constrained.

Traversable-wormhole protocols are a special case, not a contradiction. In those protocols, the system is modified by an allowed interaction, often described as a coupling between the two sides. That coupling changes the causal structure in the dual description and permits a teleportation-like process. But this is not entanglement alone doing the communication. It requires additional dynamics. The protocol remains compatible with NCT because the communication channel is supplied by permitted interactions or classical coordination, not by bare entanglement.

This point is central for quantum computers. A quantum processor may simulate a traversable-wormhole-like teleportation process. But the processor does so by implementing a specific circuit, Hamiltonian, or coupling. The observed transfer is not a violation of non-communication. It is an engineered quantum information process with a dual geometric interpretation.

Thus ER=EPR does not erase NCT. It deepens its importance. If entanglement is geometry, then NCT becomes a principle governing which geometries are causally usable and which are only relationally connected. Entanglement may build a bridge, but NCT says whether that bridge can carry a message. For ordinary entanglement, the answer is no.

7.5 The bridge as geometry, not a free communication channel

The most common misunderstanding of ER=EPR is to imagine that entangled particles are connected by tiny tunnels through which information secretly travels. This picture is too crude. It imports classical communication imagery into a quantum-gravitational conjecture that is more subtle. The bridge in ER=EPR is not a hidden wire. It is a geometric representation of entanglement, and in the ordinary case it does not allow signals to pass.

A better analogy is the difference between topology and traffic. Two regions may be connected in a mathematical structure, but that does not mean a vehicle can travel between them. Whether passage is possible depends on causal structure, energy conditions, dynamics, and boundary interactions. Similarly, two quantum systems may be entangled, but that does not mean one observer can send a chosen message to the other. Whether communication is possible depends on operations beyond shared entanglement.

This distinction also prevents ER=EPR from becoming a vague metaphor. The bridge must do explanatory work. It should correspond to measurable or calculable features of the entangled state: entropy, mutual information, complexity, scrambling, correlation functions, and reconstructability. In holographic settings, these quantities can be related to geometric objects such as areas, lengths, volumes, horizons, and entanglement wedges. The bridge is meaningful when it organizes such relations better than a non-geometric description would.

For example, in a holographic system, entanglement entropy may be related to the area of an extremal surface:

S_A = Area(gamma_A)/(4*G_N)

This formula expresses a profound link between information and geometry. The amount of entanglement associated with a boundary region is encoded by a geometric area in the bulk. If such relations hold robustly, then geometry is not decorative language. It is a compact and predictive way of describing the entanglement structure.

But none of this turns the bridge into a free communication channel. A non-traversable bridge can still have length, area, volume, and dynamics. It can grow in complexity. It can encode correlations. It can be part of a real emergent geometry. Yet it remains causally closed to direct signaling unless additional conditions are introduced.

This is the mature reading of ER=EPR. Entanglement may be geometric, but geometry is not automatically communicative. Connection is not the same as passage. Relation is not the same as signal. The bridge is real, if the conjecture is correct, as an emergent or dual geometric structure. But its reality is bounded by the same non-communication principle that governs ordinary entangled systems.

7.6 What remains conjectural

ER=EPR is one of the most fertile ideas in modern quantum gravity, but much of it remains conjectural. The strongest evidence comes from special theoretical settings, especially holographic models in which a gravitational bulk is dual to a lower-dimensional quantum boundary theory. In such systems, the relation between entanglement and geometry can be made precise. But our universe is not simply a textbook anti-de Sitter space, and ordinary

laboratory entanglement does not automatically come with directly measurable wormhole geometry.

Several questions remain open. First, how general is ER=EPR? Does every entangled pair have some kind of Planck-scale bridge, or does the bridge language apply only to special highly entangled gravitational systems? Second, what determines the geometry associated with a given entangled state? Entanglement alone is not a single number. It has structure, pattern, multipartite organization, complexity, and dynamics. Not every entangled state may correspond to a smooth geometric bridge.

Third, what is the status of the bridge? Is it literal spacetime geometry, an emergent effective description, a dual mathematical representation, or a metaphor that becomes precise only in certain limits? These options are not equivalent. A literal bridge would imply that entangled systems possess a geometric relation in a strong ontological sense. An emergent bridge would mean that geometry appears only at collective scales or in special code subspaces. A dual description would mean that the quantum and geometric accounts are equivalent ways of computing the same observables. A metaphor would be weaker and less physically binding.

Fourth, what experimental signatures could distinguish ER=EPR from ordinary quantum mechanics plus useful geometric language? This is where quantum computers enter the story. They may test whether increasingly large entangled systems exhibit holographic behavior, scrambling, error-correcting reconstruction, and teleportation dynamics that match geometric predictions. But even then, the evidence will initially be model-based. A quantum computer can instantiate the qubit-side dynamics, but whether the emergent “It” deserves the name geometry must be judged by robustness, scaling, and independent observables.

Finally, ER=EPR must remain compatible with NCT. Any version that permits free signaling through entanglement alone is ruled out. This constraint is not a weakness. It is what allows ER=EPR to coexist with both quantum mechanics and relativity.

The sober conclusion is that ER=EPR is not experimentally confirmed as a universal fact, but it is more than a slogan. It is a research program linking entanglement, black holes, wormholes, holography, quantum error correction, complexity, and the emergence of spacetime. Its promise is enormous: it may turn the EPR paradox from a threat to locality into a clue that locality itself is built from entanglement. Its limitation is equally clear: whatever bridge entanglement builds, it cannot become a forbidden message.

8. Holography and the Geometry of Quantum Information

8.1 AdS/CFT as the organizing framework

Holography provides the most developed framework in which quantum information and spacetime geometry are treated as two sides of one physical structure. The central example is AdS/CFT, where a gravitational theory in a higher-dimensional anti-de Sitter bulk is equivalent to a conformal quantum field theory living on its lower-dimensional boundary. The astonishing feature of this correspondence is that a theory with gravity and geometry can be described by a theory without gravity on the boundary. Bulk spacetime is not simply assumed; it is reconstructed from boundary quantum degrees of freedom.

This is the context in which ER=EPR becomes more than a speculative slogan. If a boundary quantum state has a dual gravitational geometry, then patterns of entanglement in the boundary theory may determine connectivity, distance, horizons, and bulk structure. The “It” of spacetime is not fundamental in this description. It is encoded in the “Qubit” structure of the boundary theory. Geometry becomes a macroscopic language for organized entanglement.

AdS/CFT is not automatically a direct description of our observed universe. Our universe appears closer to de Sitter than anti-de Sitter on cosmological scales. Nevertheless, AdS/CFT is the cleanest controlled laboratory for studying how spacetime can emerge from quantum information. It gives physicists a setting where statements about entanglement, entropy, black holes, and geometry can be made mathematically precise.

The organizing idea is that the bulk and boundary are not two separate systems communicating across a wall. They are two equivalent descriptions of one underlying physics. A boundary state can encode a bulk geometry. Bulk gravitational events can correspond to boundary quantum evolution. A black hole in the bulk can correspond to a thermal or chaotic state in the boundary theory. A bridge in the bulk can correspond to entanglement between boundary systems.

This duality shifts the meaning of space. Instead of thinking of entanglement as something located inside spacetime, holography suggests that spacetime location itself may be reconstructed from entanglement. The geometry is not the container of quantum information; it is a derived expression of quantum information.

8.2 Eternal AdS black holes and thermofield double states

The eternal AdS black hole gives one of the clearest examples of the entanglement-geometry relation. In its maximally extended form, the black hole has two exterior regions connected by an Einstein-Rosen bridge. From the boundary perspective, this two-sided geometry is described by two quantum systems prepared in a special entangled state called the thermofield double state.

A schematic form of the thermofield double state is:

|TFD> = sum_n exp(-beta*E_n/2) |n>_L |n>_R / sqrt(Z)

Here L and R label the left and right boundary systems. The index n labels energy eigenstates. The factor exp(-beta*E_n/2) gives thermal weighting. Z is the normalization. The important point is that the two boundary systems are entangled in a precise pattern. Each side alone appears thermal, but the combined state is pure.

This structure closely parallels the Bell-pair lesson, but on a vastly richer scale. For a Bell pair, the whole state is pure while each part is locally mixed. For the thermofield double, the combined left-right state is pure while each boundary system individually appears thermal. The thermal character of each side is not due to ignorance about an ordinary classical ensemble. It arises from tracing out the other side of an entangled pure state.

The geometric dual is a two-sided black hole. The entanglement between the two boundary theories is represented in the bulk by the bridge connecting the two exterior regions. The bridge is not traversable in the ordinary eternal black hole case. This preserves the Non-Communication Theorem. The two sides are deeply correlated, but one side cannot send a message to the other through the bridge without additional dynamics.

This example is central because it makes ER=EPR concrete. Entanglement is not merely accompanied by geometry. Entanglement helps define the geometry. The connectedness of the bulk is associated with the entangled structure of the boundary state. If the entanglement is changed, the dual geometry changes. If the entanglement is removed in the right way, the geometry may disconnect.

The thermofield double therefore provides a prototype for It from Qubit. The “It” is the two-sided black hole geometry. The “Qubit” side is the entangled boundary quantum state. The bridge between them is not a metaphor but a duality relation inside a controlled theoretical framework.

8.3 Ryu-Takayanagi entropy and area from entanglement

The Ryu-Takayanagi relation is one of the most important clues that geometry is built from entanglement. It relates the entanglement entropy of a boundary region to the area of a surface in the bulk. In schematic form:

S_A = Area(gamma_A)/(4*G_N)

Here S_A is the entanglement entropy of boundary region A. The surface gamma_A is the appropriate minimal or extremal surface in the bulk whose boundary matches the boundary of

region A. G_N is Newton's gravitational constant. The formula resembles the black hole entropy-area relation, but applies more broadly in holographic settings.

The conceptual meaning is profound. Entropy, a quantum-information quantity, is equal to area, a geometric quantity. The formula says that the amount of entanglement associated with a boundary region is measured by a bulk surface area. This is one of the clearest mathematical expressions of It from Qubit: geometry knows about entanglement because geometry is partly made from entanglement.

If the entanglement entropy changes, the corresponding bulk surface changes. If the boundary state is altered, the bulk geometry responds. This suggests that distances, areas, and connectivity are not primitive. They are encoded in the structure of the quantum state.

This also helps explain why black holes are central to the field. Black hole entropy already suggested that gravitational systems count information in terms of area rather than volume. Holography generalized that lesson. The information content of a region with gravity may be encoded on a lower-dimensional surface. Ryu-Takayanagi then gave a sharper relation: boundary entanglement entropy corresponds to bulk geometric area.

The formula also reframes the EPR problem. If entanglement is connected to geometry, then nonclassical quantum correlations are not merely an embarrassment for locality. They may be the raw material from which locality is assembled. Spacetime may be stitched together by entanglement patterns. A decrease in entanglement may correspond to a stretching or tearing of geometric connection.

However, the formula does not imply that entanglement can transmit signals. Area is not a communication channel. A surface may encode entropy and connectivity without permitting faster-than-light messaging. The Non-Communication Theorem remains intact. Entanglement can contribute to geometry while still being locally unreadable as a chosen message.

8.4 Entanglement wedge reconstruction

Entanglement wedge reconstruction deepens the holographic picture by showing how bulk information can be encoded redundantly in boundary regions. For a given boundary region A, there is a corresponding bulk region called its entanglement wedge. Under suitable conditions, operators or information inside that wedge can be reconstructed from the boundary degrees of freedom in A. This means that the boundary does not merely store a flat image of the bulk. It encodes bulk information in a quantum error-correcting way.

This is a major shift in how spacetime is understood. In ordinary local field theory, one expects information in a region to be stored in that region. In holography, bulk information may be reconstructable from different boundary regions, depending on the entanglement structure.

The same bulk operator may have multiple boundary representations. This redundancy resembles quantum error correction, where logical information can be recovered even if part of the physical system is lost.

The entanglement wedge is determined by both geometry and entropy. Its boundary is related to extremal surfaces. As the boundary region changes, the entanglement wedge changes. Information that is reconstructable from one boundary region may become inaccessible from another. The geometry of the wedge therefore reflects the informational access structure of the boundary state.

This idea is crucial for It from Qubit because it suggests that bulk locality is not fundamental. A bulk point is not simply stored at one boundary location. It is encoded nonlocally across boundary degrees of freedom. What appears as a local object in the bulk may correspond to a distributed quantum code on the boundary. Locality in the emergent spacetime arises from the organization of the encoding.

Entanglement wedge reconstruction also helps clarify why holographic geometry is robust. If bulk information is protected like a quantum error-correcting code, then small errors or erasures in the boundary do not necessarily destroy the bulk. This gives a possible explanation for why spacetime appears smooth and stable despite being built from microscopic quantum degrees of freedom.

The connection to the Non-Communication Theorem remains important. Redundant reconstruction is not arbitrary signaling. Boundary regions can reconstruct bulk information only according to the rules of the code and the causal structure of the duality. The encoding may be nonlocal, but it does not allow forbidden communication. The code structure supports emergent geometry while preserving quantum consistency.

8.5 Holographic quantum error correction

Holographic quantum error correction provides one of the most concrete mechanisms by which spacetime may emerge from quantum information. In an ordinary quantum error-correcting code, a logical qubit is encoded into many physical qubits. The logical information is not stored in any single physical qubit. It is distributed across the larger system in such a way that the loss of some physical qubits does not destroy the encoded information.

Holography appears to work similarly. Bulk degrees of freedom are like logical information. Boundary degrees of freedom are like physical qubits. The bulk is not stored point-by-point on the boundary. Instead, it is encoded redundantly and nonlocally. Different boundary regions may be able to reconstruct the same bulk information if they contain enough of the relevant entanglement structure.

This explains several otherwise puzzling features of AdS/CFT. It explains how a lower-dimensional boundary theory can encode a higher-dimensional bulk. It explains how bulk locality can emerge even though the boundary encoding is nonlocal. It explains why black hole interiors and entanglement wedges can be reconstructed in subtle, state-dependent ways. It also explains why geometry can be stable under small perturbations: the code protects the logical bulk.

A simple schematic is:

physical qubits on boundary -> encode -> logical bulk degrees of freedom

The arrow is not a spatial map. It is an encoding map. The emergent bulk is a logical structure supported by the entangled boundary system.

This is a powerful way to understand It from Qubit. The “It” is not produced by arranging qubits into a literal miniature model of space. It arises when the qubits implement an error-correcting structure whose logical degrees of freedom behave like fields and geometry in a bulk spacetime. The geometry is the code’s emergent organization.

Quantum computers may eventually test this idea directly. A quantum processor can implement small quantum error-correcting codes, tensor-network-inspired holographic codes, and scrambling dynamics. It can test whether logical information is reconstructable from multiple regions, whether entanglement entropy follows area-like rules, and whether perturbations behave like bulk excitations. Such experiments would not prove that our universe is a quantum code, but they would instantiate code-based emergent geometry in controllable physical systems.

The essential point is that holographic error correction turns emergence into mechanism. It gives a concrete answer to how spacetime could arise from qubits: through protected, redundant, entanglement-structured encoding.

8.6 Geometry as an encoded informational structure

The cumulative lesson of holography is that geometry may be an encoded informational structure rather than a primitive background. Distances, areas, horizons, bridges, and wedges may arise from the entanglement pattern of underlying quantum degrees of freedom. In this picture, spacetime is not the stage on which quantum information acts. Spacetime is one of the large-scale forms that quantum information can take.

This does not mean geometry is unreal. Emergent does not mean imaginary. A phonon is emergent, but real within the physics of a crystal. Temperature is emergent, but real within thermodynamics. Likewise, a holographic bulk geometry may be emergent and real as an effective, predictive, operational structure. The question is not whether the geometry is

fundamental. The question is whether it has stable observables, causal rules, reconstructable content, and explanatory power.

Holography suggests that geometry becomes real when the underlying quantum state supports the right code structure. A random entangled state may not produce a smooth spacetime. A specially organized entangled state may. Smooth geometry appears to require entanglement with the right pattern, strength, redundancy, and dynamics. It is not entanglement alone, but structured entanglement, that seems capable of building spacetime.

This distinction will matter for quantum computers. A quantum processor can entangle qubits easily. But merely entangling qubits does not instantiate geometry. To approach It from Qubit, the processor must instantiate a structured many-body state or dynamics whose observables match geometric predictions. It must show area-like entropy behavior, scrambling, reconstructability, and scaling. The geometry must be more than a visualization of the circuit. It must be the best operational description of the quantum system's behavior.

The Non-Communication Theorem remains the causal boundary of this encoded geometry. Even if entanglement builds bridges, wedges, or emergent distances, it does not permit free signaling. Causal structure must emerge alongside geometric structure. A viable It from Qubit program must explain not only how space arises, but why forbidden messages do not.

Holography therefore provides the central bridge between EPR and quantum computers. EPR showed that quantum reality is not locally separable. Bell showed that this is experimentally real. NCT showed that causality survives. ER=EPR proposed that entanglement can be geometric. Holography explains how that could work: geometry may be the encoded, error-corrected, informational form of a quantum state. The next question is whether such geometry can be physically instantiated in engineered quantum systems.

9. It from Qubit: From Quantum Information to Spacetime

9.1 Wheeler's "It from Bit" and the quantum revision

John Archibald Wheeler's phrase "It from Bit" expressed the idea that physical reality may arise from acts of information, distinction, and measurement. The "It" is the physical world: particles, fields, events, spacetime, and the objects of experience. The "Bit" is the informational distinction: yes or no, 0 or 1, the answer to a question. Wheeler's slogan did not reduce reality to ordinary computation in a simplistic way. It suggested that the physical world and the informational structure by which it becomes definite are inseparable.

"It from Qubit" is the quantum revision of this idea. The fundamental informational unit is no longer the classical bit, which has a definite value of 0 or 1, but the qubit, which can exist in

superposition, become entangled, and participate in nonclassical correlations. This change is not cosmetic. A universe built from bits would still be compatible with a classical hidden registry of definite values. A universe built from qubits begins with relational structure, superposition, measurement context, and entanglement.

The transition from bit to qubit therefore changes the meaning of emergence. In a classical informational universe, one might imagine spacetime and matter arising from a vast digital code. In a quantum informational universe, spacetime may arise not merely from discrete entries in a code, but from the entanglement structure among quantum degrees of freedom. The fundamental substrate is not a list of local facts. It is a state space whose parts can be nonseparably related.

This is why It from Qubit belongs naturally with EPR, Bell, ER=EPR, holography, and the Non-Communication Theorem. EPR showed that quantum theory contains nonclassical relational structure. Bell tests showed that this structure is experimentally real. Holography showed that geometry may be encoded in quantum information. ER=EPR suggested that entanglement itself may be geometric. It from Qubit gathers these clues into a single research direction: spacetime may emerge from quantum information, and entanglement may be the stitching principle.

The quantum revision is therefore deeper than replacing one unit of information with another. It changes the ontology. The world is not first a set of objects in space that later exchange information. Instead, the informational relations may be prior, and space may be the large-scale expression of their organization.

9.2 Why qubits are not merely abstract bookkeeping

A qubit is often introduced as a mathematical object: a two-level quantum system described by amplitudes. In its simplest form, a qubit can be written as:

$|\psi\rangle = a|0\rangle + b|1\rangle$

with:

$|a|^2 + |b|^2 = 1$

This notation can make qubits look like abstract bookkeeping. But physical qubits are not merely symbols. They can be realized by photons, ions, atoms, superconducting circuits, nuclear spins, quantum dots, or other physical systems. They can be prepared, manipulated, entangled, measured, decohered, corrected, and used in protocols. Their behavior is not optional mathematics. It is experimentally accessible physics.

The importance of qubits lies in what they can do that classical bits cannot. A classical bit has one definite value at a time. A qubit can exist in a superposition relative to a measurement

basis. Multiple qubits can become entangled so that the state of the whole cannot be reduced to the independent states of the parts. This is the core feature needed for It from Qubit. If spacetime emerges from quantum information, it is not emerging from isolated qubits as independent beads. It is emerging from the structure of entanglement, correlation, code, and dynamics among them.

The distinction between abstract bookkeeping and physical instantiation matters especially for quantum computers. A classical computer can simulate the equations of a quantum system, but the underlying hardware remains classical at the logical level. Its bits do not become the entangled system being simulated. A quantum computer, by contrast, can physically instantiate qubits and entangling operations. Its internal state can itself be a many-body quantum state. When it simulates certain quantum systems, the separation between representation and realization becomes more subtle.

This does not mean every quantum computation creates a universe or a spacetime. Most quantum circuits do not instantiate anything resembling geometry. A random entangled state may be complex without being geometric. A small engineered circuit may reproduce selected features of a holographic model without establishing a robust bulk. But qubits on a quantum processor are still physically real quantum degrees of freedom. If they are arranged into the right entanglement pattern, error-correcting structure, and dynamics, then they may instantiate the qubit-side substrate from which a spacetime-like “It” can be operationally inferred.

Qubits are therefore not passive labels in a theory. They are candidate building blocks of emergent physical structure. The question is not whether qubits are real. The question is what kinds of collective reality can arise from them.

9.3 What it means for “It” to arise from entanglement

For “It” to arise from entanglement means that the apparent objects and geometry of a physical world are not fundamental starting points, but emergent structures defined by patterns of quantum relation. In ordinary classical thinking, one begins with space, places objects inside it, and then allows the objects to interact. In the entanglement-first picture, one begins with quantum degrees of freedom and asks whether spatial distance, adjacency, connectivity, and geometry can be reconstructed from how those degrees of freedom are correlated.

This reverses the usual explanatory order. Instead of saying that two particles are entangled because they are located in a common spacetime and once interacted, the stronger It from Qubit view asks whether the meaning of spacetime separation itself depends on the entanglement network. Systems that are highly entangled may be close in an emergent geometric sense. Systems with little or no mutual entanglement may be far apart, disconnected, or outside one another’s reconstructable domain.

This does not mean that entanglement alone is sufficient. Entanglement has many forms. A chaotic random entangled state may not resemble a smooth spacetime. Smooth geometry appears to require organized entanglement: specific scaling of entropy, redundancy of encoding, local reconstructability, stable dynamics, and causal structure. The emergence of “It” requires the right pattern, not merely the existence of correlation.

A useful schematic hierarchy is:

qubits -> entanglement -> code structure -> emergent locality -> geometry -> spacetime physics

Each arrow represents a nontrivial step. Qubits must be entangled in the correct way. Entanglement must support a code. The code must define logical degrees of freedom that behave locally in an emergent bulk. The bulk must exhibit geometry, causality, and dynamics. Only then does “It” arise in the strong sense.

The Non-Communication Theorem must remain active throughout this hierarchy. If emergent geometry arises from entanglement, then causal structure must arise with it. It is not enough to build connection. The theory must also explain why connection does not automatically become forbidden communication. In this sense, NCT is not merely a rule added afterward. It is part of the structure that distinguishes physically viable geometry from uncontrolled nonlocality.

To say that “It” arises from entanglement is therefore to make a disciplined claim: physical geometry may be the stable, error-corrected, causally constrained expression of structured quantum correlation. Entanglement is not a ghostly force across pre-existing space. It may be part of the machinery by which space becomes meaningful.

9.4 Emergence versus simulation

The difference between emergence and simulation is central to evaluating quantum computers as laboratories for It from Qubit. A simulation represents one system by another. A classical computer simulating a black hole does not create a black hole. It stores numbers and evolves them according to programmed rules. The simulated black hole may be mathematically accurate, but the computer does not possess an event horizon, Hawking radiation, or spacetime curvature in the physical sense.

A quantum computer complicates this distinction because it does not merely calculate quantum amplitudes using classical bits. It can realize a physical quantum state whose internal structure follows the same rules as the target system. If a quantum processor implements a Hamiltonian that is dual to a gravitational model, the processor is not just drawing a picture of the model. It is instantiating the quantum dynamics on the boundary side of the duality. The question then becomes whether the corresponding bulk geometry should be regarded as merely simulated or emergent from the actually instantiated quantum state.

A cautious answer is necessary. A quantum computer running a small holographic circuit is not automatically making literal spacetime. It is physically realizing a quantum process that may have a geometric dual description. The geometry becomes more than a metaphor only if it has robust, independent, and scalable signatures. These may include entanglement-area behavior, scrambling, teleportation asymmetry, operator growth, code-subspace reconstruction, and stability under perturbation.

Emergence requires that the higher-level description has explanatory power not reducible to arbitrary visualization. A weather simulation produces images of storms, but the computer does not become wet. A crystal supports phonons, and the phonons are real emergent excitations because they are measurable, predictive, and constrained by the physical medium. A quantum-computer holographic bulk would need to be more like the phonon case than the weather-map case. It would need to be an emergent operational structure of the actual quantum device, not merely a diagram imposed from outside.

This distinction can be summarized as:

classical simulation = symbolic representation of another system

quantum simulation = physical quantum dynamics representing another quantum system

holographic instantiation = physical quantum dynamics whose dual description behaves as emergent geometry

The third category is the target of It from Qubit. It is not yet fully achieved, but it defines the experimental ambition. Quantum computers may provide a path from simulation toward instantiation if the emergent geometric description becomes necessary, robust, and testable.

9.5 Bulk reality as an operational description

In holography, the bulk is the gravitational spacetime description, while the boundary is the quantum theory from which the bulk is encoded. The question of bulk reality is subtle. If the boundary theory is complete, is the bulk merely a convenient fiction? Or is it real because it captures the operational structure of what observers, excitations, and measurements would experience inside the emergent geometry?

A useful answer is that bulk reality can be operational rather than fundamental. Something can be emergent and still real. Temperature is not a property of a single molecule, but it is real for a gas. A phonon is not a fundamental particle, but it is real in a crystal. A wave in water is not separate from the water molecules, but it is real as a stable, measurable pattern. In the same way, a holographic bulk may not be fundamental, but it can be real if it provides a stable, predictive, reconstructable description of the quantum state.

Operational bulk reality requires several conditions. First, bulk observables must correspond to boundary observables in a controlled way. Second, bulk locality must emerge approximately, so that events in the bulk behave as if they occur in a geometric spacetime. Third, the geometry must have measurable consequences, such as entropy-area relations, causal wedges, correlation decay, and reconstruction rules. Fourth, the description must remain consistent under time evolution and perturbation.

This view avoids two extremes. One extreme says that only the boundary qubits are real and the bulk is just a calculation trick. The other says that the bulk must be fundamental in the same sense as classical spacetime was once assumed to be. Operational realism takes a middle path. The bulk is real when it is the correct emergent level of description for the quantum system, even if it is not fundamental.

Quantum computers may eventually make this issue experimental. If a processor realizes a boundary quantum state whose observables are best organized by an emergent bulk description, then that bulk gains operational reality inside the experiment. It may not be a macroscopic tunnel in the laboratory. It may not curve the room. But it may be real as the emergent geometry of the quantum system.

The Non-Communication Theorem remains decisive. A bulk description that allowed forbidden signaling would not be a valid emergent spacetime. Operational bulk reality must include causal discipline. Geometry must come with light-cone-like constraints, not merely with connectivity.

Thus “bulk reality” in It from Qubit is not a mystical claim. It is the claim that a sufficiently structured quantum system can support a higher-level geometric description with predictive, reconstructable, and causally consistent content.

9.6 The proposed hierarchy: qubit, code, geometry, causality

The It from Qubit program can be organized as a hierarchy. At the base are qubits or more general quantum degrees of freedom. These are not yet spacetime. They are physical carriers of quantum state. Above them is entanglement, which relates the degrees of freedom in ways that cannot be reduced to independent local properties. Above entanglement is code structure, where quantum information is protected, distributed, and reconstructable. Above code structure is emergent geometry, where the informational relations acquire the form of distance, area, region, and connection. Above geometry is causality, where the emergent spacetime supports ordered communication, horizons, and no forbidden signaling.

The hierarchy can be written schematically as:

qubit -> entanglement -> quantum error-correcting code -> bulk geometry -> causal spacetime

This is not a simple linear construction in practice. The layers constrain one another. The code structure determines which geometry can emerge. The geometry determines which causal relations make sense. Causality limits which operations can be interpreted as physical communication. Entanglement supports geometry, but NCT prevents entanglement from becoming uncontrolled signaling.

The hierarchy also clarifies what quantum computers must demonstrate. A machine that merely contains qubits has only reached the first layer. A machine that entangles qubits has reached the second. A machine that implements robust logical encoding reaches the third. A machine whose encoded observables behave geometrically reaches the fourth. A machine whose emergent geometry has consistent causal structure reaches the fifth. Only at that point does It from Qubit become a physically instantiated program rather than a guiding metaphor.

This hierarchy also distinguishes different kinds of evidence. Bell tests confirm real entanglement. Quantum error-correcting experiments confirm protected logical structure. Holographic simulations test whether code and entanglement can mimic geometry. Traversable-wormhole-inspired protocols test whether teleportation dynamics can match a geometric causal story. Gravity-mediated entanglement experiments would test whether gravity itself participates in quantum information. Each experiment probes a different level of the hierarchy.

The final level, causality, returns the paper to the Non-Communication Theorem. Any emergent spacetime must explain why observers cannot use entanglement alone to signal outside the light cone. If the theory builds connection but not causal constraint, it fails. If it builds geometry but permits forbidden messages, it is not our physics. The success of It from Qubit depends not only on deriving space from entanglement, but also on deriving the disciplined causal order that makes spacetime physically coherent.

The central claim is therefore not simply that qubits make geometry. The stronger and more careful claim is that structured qubits, organized by entanglement and quantum error correction, may instantiate emergent geometry whose causal behavior is bounded by the Non-Communication Theorem. In that sense, the “It” is not just from qubit. It is from qubit, code, and no-signaling together.

10. Quantum Computers as Laboratories for Emergent Spacetime

10.1 Quantum processors as physical instantiators

Quantum computers are important to the It from Qubit program because they are not merely calculators of quantum theory. They are physical quantum systems that can instantiate qubits, entanglement, unitary evolution, measurement, decoherence, and error correction. A classical

computer can represent a quantum state symbolically, but the machine itself does not become the quantum system it simulates. A quantum processor is different. Its internal degrees of freedom can be placed into the same kind of many-body entangled structure that the theory describes.

This distinction gives quantum computers a special role in the study of emergent spacetime. If spacetime-like geometry can arise from structured entanglement, then a quantum processor may physically realize the lower-level substrate from which a geometric description emerges. The processor does not have to create a visible tunnel in the laboratory. It must instantiate the qubit-side dynamics with enough fidelity that the corresponding geometric interpretation becomes operationally meaningful.

The important word is instantiate. A quantum computer running a holographic circuit does not merely draw a wormhole on a screen. It prepares a quantum state, applies entangling gates, implements effective interactions, and produces measurement statistics. If those statistics match the predictions of a dual gravitational model, then the quantum side of the duality has been physically realized. The emergent geometry, if justified, is not located as a miniature object inside the chip. It is the higher-level description of the chip's quantum state and dynamics.

This is why quantum computers may become laboratories for quantum gravity even though their devices are small and cold rather than astronomical and massive. Quantum gravity is not only about large gravitational fields. It is also about the relation between quantum information and geometry. If a controllable many-qubit system can reproduce the informational structure of a black hole, a wormhole protocol, or a holographic code, then it gives experimental access to part of the quantum-gravity problem.

However, physical instantiation should not be confused with automatic proof. A quantum processor can instantiate an entangled circuit without instantiating a smooth spacetime. It can instantiate a toy model without proving the model describes our universe. It can instantiate selected observables without establishing full holographic duality. The claim must be earned by robustness, scaling, and independent checks.

The most cautious position is therefore also the most productive: quantum processors can instantiate the quantum information side of candidate spacetime-emergence models. Whether the corresponding "It" is real geometry depends on what the instantiated system does.

10.2 SYK-like models and holographic chaos

The Sachdev-Ye-Kitaev model, usually abbreviated SYK, has become one of the most important toy models for studying quantum chaos, black-hole-like dynamics, and holography. It describes many interacting quantum degrees of freedom with random all-to-all couplings. Despite its apparent simplicity, the model exhibits features that resemble aspects of near-AdS2 gravity and

black hole scrambling. This makes it attractive as a bridge between quantum computation and emergent spacetime.

The reason SYK-like models matter is that black holes are believed to be among the fastest scramblers in nature. Scrambling means that initially localized quantum information becomes rapidly distributed across many degrees of freedom in such a way that it cannot be recovered from small subsystems. In a black hole, information thrown in appears to spread across the horizon degrees of freedom. In a many-qubit model, information inserted into one qubit can spread into a complex nonlocal pattern across the full register.

A schematic scrambling process can be written as:

local input -> many-body unitary evolution -> delocalized encoded information

For holography, the relevant question is whether this delocalized quantum information has a dual geometric meaning. In black-hole language, the growth and spread of operators may correspond to motion into the bulk, approach to a horizon, or growth of an interior. In quantum-information language, the same process is described by operator growth, entanglement growth, and increasing circuit complexity.

SYK-like models are useful because they are quantum many-body systems with strong chaos and solvable or semi-solvable limits. They give theorists a controlled place to connect concepts such as thermalization, scrambling, out-of-time-order correlations, spectral statistics, and emergent gravitational dynamics. They are not full models of our universe, but they are laboratories for the black-hole information problem in reduced form.

Quantum computers enter because classically simulating strongly entangled chaotic systems becomes rapidly difficult as system size grows. A quantum processor can implement a version of the model directly, at least in principle. This creates the possibility of testing whether the predicted scrambling and teleportation signatures appear in real quantum hardware.

The challenge is that genuine SYK dynamics are hard to implement on near-term devices. The model involves many-body interactions and complex couplings. Present experiments often require simplification, sparsification, compilation, or learning procedures to reduce the circuit depth. These reductions are practical, but they create interpretive risk. If the simplified model loses the chaos, thermalization, or spectral properties that made SYK holographically interesting, then the resulting experiment may show teleportation-like behavior without genuinely probing black-hole-like dynamics.

Therefore, the next generation of experiments must show not merely that a signal can be recovered, but that the recovery depends on the same chaotic and scrambling structure that supports the gravitational interpretation.

10.3 Traversable-wormhole-inspired teleportation

Traversable-wormhole-inspired teleportation sits at the intersection of quantum information and geometry. In ordinary quantum teleportation, Alice transfers an unknown quantum state to Bob using shared entanglement and classical communication. In holographic traversable-wormhole protocols, a related process can receive a dual gravitational description: a message appears to pass through a wormhole after a specific interaction makes the bridge traversable.

The key point is that traversability is not free. A non-traversable Einstein-Rosen bridge cannot transmit a message. To make the dual bridge traversable, the two sides must be coupled in a special way. In the quantum description, this coupling is an allowed interaction between the two boundary systems. In the gravitational description, the interaction modifies the effective causal structure so that a signal can pass through the bridge. The process remains causal because the required coupling or communication is part of the physical protocol.

A simplified structure is:

entangled left-right system + perturbation + coupling -> recoverable signal

The perturbation represents the injected message. The coupling represents the operation that makes recovery possible. The recovered signal is not evidence that bare entanglement carried a message by itself. It is evidence that entanglement plus a specified interaction can implement a teleportation-like process with a geometric dual.

This is why traversable-wormhole protocols are compatible with the Non-Communication Theorem. Without the coupling, the bridge remains non-traversable. With the coupling, the protocol includes an allowed causal mechanism. The message is not traveling faster than light through unassisted entanglement. It is being transmitted through a structured quantum process whose gravitational description resembles passage through a wormhole.

Quantum computers are natural platforms for these experiments because they can implement the entangled state, the perturbation, the coupling, and the measurement sequence. Instead of waiting for astrophysical wormholes, researchers can build the quantum circuit corresponding to the boundary dynamics. The device then tests whether the predicted recovery, timing, and dependence on coupling sign occur.

The strongest version of such an experiment would show several linked features. The signal should be recoverable only under the correct coupling. The recovery should depend on timing in a way predicted by the dual model. The dynamics should show scrambling rather than simple direct transmission. The behavior should be asymmetric in the manner expected from traversability. The effect should scale with system size and persist under less engineered conditions.

When these features appear together, the wormhole interpretation becomes more compelling. If only a small recovery signal appears in a heavily optimized circuit, the result is still interesting, but it may be better described as a teleportation experiment with a suggestive analogy. The difference between analogy and instantiation depends on the full structure of the dynamics.

10.4 Lessons from the 2022 quantum-processor experiment

The 2022 quantum-processor wormhole experiment was significant because it demonstrated that current quantum hardware can implement a small, carefully designed model whose dynamics have a traversable-wormhole interpretation. The experiment used a reduced SYK-like system mapped onto a small number of qubits. A perturbation was introduced, an interaction between the two sides was applied, and a signal was recovered in a way interpreted through the dual language of teleportation and traversable wormhole dynamics.

The experiment was symbolically important because it made the It from Qubit program tangible. A quantum processor was not merely used to calculate an equation about a hypothetical wormhole. It physically implemented a quantum circuit corresponding to a model in which the same process can be described as teleportation on one side and wormhole passage on the other. This is precisely the kind of boundary between simulation and instantiation that the field must now explore.

The lesson is not that a literal macroscopic wormhole was created. No spacetime tunnel opened inside the laboratory. No object traveled through a gravitational throat. The device implemented the quantum-information side of a dual model. The “wormhole” was the emergent or dual description of the dynamics, not a visible general-relativistic structure in the room.

This distinction does not make the experiment trivial. Many important physical ideas begin in controlled toy systems. The first demonstrations of quantum teleportation did not teleport people; they verified a protocol. The first quantum simulations of materials do not reproduce all of chemistry; they test reduced Hamiltonians. Similarly, a small traversable-wormhole-inspired circuit can be valuable if it verifies elements of the duality structure.

However, the experiment also showed the limits of near-term quantum gravity simulation. The system was very small. The model had to be simplified. The circuit was selected and optimized to fit available hardware. The degree to which the system displayed genuine chaotic SYK behavior was debated. These limitations matter because the gravitational interpretation depends on more than signal recovery. It depends on the presence of the right many-body dynamics.

The enduring lesson is therefore balanced. The experiment opened a door by showing that quantum processors can instantiate model dynamics relevant to ER=EPR and holographic

teleportation. It did not close the case by proving that spacetime is made of qubits or that wormholes have been experimentally confirmed. It marked the beginning of a research path, not the end.

10.5 Criticisms: small size, hand-tuning, and weak chaos

The main criticisms of early quantum-processor wormhole experiments concern size, hand-tuning, and weak chaos. These criticisms do not necessarily invalidate the experiments, but they define the standard future work must meet.

The first issue is small size. A system with only a few qubits can demonstrate a protocol, but it may not capture the collective behavior that gives black holes their distinctive physics. Black-hole-like scrambling is a many-body phenomenon. Holographic geometry is expected to emerge most clearly in large-N or many-degree-of-freedom limits. A very small system may reproduce selected equations while lacking the scale needed for robust geometry.

The second issue is hand-tuning. If a Hamiltonian or circuit is heavily optimized to produce a desired signal, then the result may reflect engineering rather than universal physics. A useful toy model is acceptable, but the gravitational interpretation becomes stronger only when the behavior arises naturally from a broad class of systems satisfying the theoretical conditions. If the effect disappears when the model is slightly changed, the claim of emergent geometry weakens.

The third issue is weak chaos. SYK-like models are valuable because of their chaotic, scrambling behavior. If a simplified version lacks thermalization, has excessive commuting structure, or fails standard diagnostics of quantum chaos, then its connection to black-hole physics becomes less convincing. A teleportation signal alone is not enough. Ordinary quantum circuits can transmit or recover information in many ways. The question is whether the recovery has the special structure predicted by holographic wormhole dynamics.

Relevant diagnostics include:

out-of-time-order correlators

operator growth

spectral statistics

thermalization behavior

scrambling time

coupling-sign dependence

size-winding behavior

reconstruction properties

These diagnostics help distinguish true holographic dynamics from generic quantum information processing. A small circuit may show a signal, but without chaos and scrambling the signal may not justify a gravitational interpretation.

The criticisms are therefore constructive. They clarify what “quantum instantiation” must mean. It is not enough to place the word wormhole on a quantum circuit. The circuit must instantiate the right class of quantum dynamics. The more the system scales, scrambles, thermalizes, reconstructs, and matches independent geometric predictions, the stronger the case becomes.

A mature field will not avoid these criticisms. It will use them as benchmarks. The next generation of experiments must be larger, less hand-crafted, more chaotic, and more independently diagnostic. Only then can the quantum processor move from suggestive demonstration toward a credible laboratory for emergent spacetime.

10.6 What larger quantum simulations must demonstrate

Larger quantum simulations must demonstrate that holographic behavior is robust rather than decorative. The goal is not simply to increase the number of qubits. The goal is to show that as the system grows, the observed dynamics increasingly match the expectations of the proposed gravitational dual. Scaling is essential because emergent geometry is not expected to be fully visible in the smallest systems. Like thermodynamics, geometry may require collective organization.

The first requirement is genuine many-body entanglement. The processor must create states whose correlations cannot be reduced to simple pairwise links or shallow circuit artifacts. The entanglement structure should support nontrivial entropy patterns, mutual information behavior, and possibly area-like scaling in appropriate code subspaces.

The second requirement is scrambling. Information injected into a small part of the system should spread across many degrees of freedom in a way consistent with chaotic dynamics. This should be visible through operator growth, recovery difficulty, out-of-time-order correlations, and sensitivity to perturbation.

The third requirement is controlled teleportation or signal recovery. A perturbation inserted on one side should be recoverable on the other only under the correct protocol. The recovery should depend on timing, coupling sign, and system dynamics in the way predicted by the traversable-wormhole model. It should not be explainable as a simple direct wire hidden in the circuit.

The fourth requirement is error-correcting structure. If the experiment is to support It from Qubit rather than mere quantum transport, it must show that information is encoded

redundantly and reconstructably. Bulk-like information should be recoverable from appropriate boundary regions, and the recovery should be stable against erasures or noise within limits.

The fifth requirement is geometric predictiveness. The emergent geometric description should do work. It should predict relations among entropy, recovery, causal order, complexity, and perturbation response. If the same data are more simply and accurately described in geometric terms than by arbitrary circuit analysis, the claim of emergent geometry becomes stronger.

The sixth requirement is compatibility with NCT. No matter how wormhole-like the dynamics become, the system must not permit communication through entanglement alone. Any successful signal transfer must depend on allowed couplings, measurements, or classical information. This is not a limitation on the experiment; it is a mark of physical consistency.

The long-term target can be summarized as:

larger qubit system -> genuine chaos -> structured entanglement -> code behavior -> geometric observables -> causal consistency

If quantum computers can climb this ladder, they will become more than tools for simulating known equations. They will become experimental arenas in which spacetime emergence can be tested as a physical process. The strongest future result would not be a headline saying that a wormhole was created. It would be a body of evidence showing that a controllable quantum system has an emergent geometric description with measurable, scalable, and causally disciplined behavior.

That is the realistic promise of quantum computers in this field. They may not directly reveal a wormhole in the sky or a tunnel on a chip. But they may show, step by step, how entanglement, scrambling, and quantum error correction can instantiate the conditions under which geometry itself becomes an emergent fact.

11. Criteria for Quantum Instantiation Into Actual Reality

11.1 Real entanglement

The first criterion for quantum instantiation is real entanglement. A quantum computer cannot instantiate It from Qubit merely by storing binary values, running a classical algorithm, or displaying a geometric analogy. It must create physical quantum states whose correlations cannot be reduced to separable local states. The qubits must not simply be synchronized, classically correlated, or programmed to imitate quantum statistics. They must occupy joint states in which the whole cannot be factored into independent parts.

For two systems A and B, separability means the joint state can be written as a mixture of product states:

rho_AB = sum_i p_i rho_A_i x rho_B_i

An entangled state cannot be written in this form. The failure of such factorization is the minimal mathematical condition for entanglement. But for experimental instantiation, the criterion must be operational. The system should demonstrate entanglement through Bell-type violations, entanglement witnesses, tomography, randomized measurements, or other diagnostics appropriate to the scale of the device.

This matters because the It from Qubit claim depends on entanglement as a physical resource, not as decorative language. A simulated bridge, emergent wedge, holographic code, or wormhole-like teleportation protocol has no foundational force unless the underlying system is genuinely quantum. The geometry, if it emerges, must emerge from nonclassical relational structure.

Real entanglement also distinguishes quantum instantiation from classical analogy. A classical computer can represent the equation:

|Phi+> = (|00> + |11>)/sqrt(2)

but the bits inside the machine are not thereby entangled. A quantum processor can physically prepare a state approximating |Phi+>. This difference is decisive. Instantiation begins when the device itself carries the quantum relation.

However, entanglement alone is not enough. Many entangled states have no known geometric meaning. A random entangled state may be highly nonclassical without behaving like spacetime. The first criterion is therefore necessary but not sufficient. Real entanglement supplies the substrate. The later criteria determine whether that substrate supports geometry, reconstruction, dynamics, and causal structure.

11.2 Dynamical implementation

The second criterion is dynamical implementation. A static entangled state is important, but emergent spacetime requires more than a frozen pattern of correlation. Geometry has dynamics. Signals move, perturbations spread, horizons form, complexity grows, and causal relations organize events. A quantum computer must therefore instantiate not only entangled states, but also controlled quantum evolution.

In practice, this means implementing a Hamiltonian, circuit, or sequence of operations corresponding to the model under investigation. The device must prepare an initial state, evolve it under specified dynamics, insert perturbations, apply couplings, and measure outcomes. The

experiment should not merely verify that entanglement exists. It should show how quantum information moves and transforms within the system.

A general unitary evolution can be written as:

|psi(t)> = U(t)|psi(0)>

with:

U(t) = exp(-iHt)

Here H is the Hamiltonian and U(t) is the time-evolution operator. In a quantum computer, U(t) may be implemented directly, approximated through gates, or simulated through a digital sequence. The key requirement is that the implemented dynamics preserve the essential structure of the target model.

This criterion is especially important for SYK-like systems and traversable-wormhole-inspired protocols. The gravitational interpretation depends on how perturbations evolve. If the implemented circuit merely moves information from input to output by an engineered shortcut, it has not instantiated holographic dynamics. If instead the information scrambles, becomes delocalized, responds to couplings in the predicted way, and is later recoverable through the proper protocol, then the experiment begins to approach physical instantiation.

Dynamical implementation must also be robust. A result that appears only after extreme fine-tuning may be interesting, but it is weaker evidence for emergent geometry. The stronger case is that a family of related Hamiltonians or circuits displays the predicted behavior. The dynamics should not be an illusion created by a single optimized construction.

In this sense, a quantum computer becomes a laboratory for emergence only when it does time-dependent quantum physics. It must not simply contain qubits. It must let them evolve in a way that realizes the model's causal, scrambling, and reconstructive structure.

11.3 Scrambling and operator growth

The third criterion is scrambling and operator growth. In black-hole-inspired quantum information, scrambling is the process by which initially localized information spreads across many degrees of freedom until it becomes inaccessible to small subsystems. This is central to the connection between quantum computers, holography, and emergent spacetime because black holes are expected to be extremely efficient scramblers.

If a quantum processor is to instantiate a black-hole-like or wormhole-like model, it must show more than ordinary entanglement. It must show that information injected into one part of the system becomes distributed across the whole in a structured, chaotic way. A local perturbation should grow into a complex operator with support on many qubits.

A schematic form is:

simple operator -> time evolution -> complex many-qubit operator

or:

$O(t) = U^{\dagger}(t)\, O\, U(t)$

At early times, O may act on one or a few qubits. After chaotic evolution, O(t) may effectively act on many qubits. This growth is not merely mathematical. It can be probed through out-of-time-order correlators, recovery protocols, randomized measurements, and sensitivity to perturbations.

Scrambling is crucial because it helps distinguish holographic dynamics from simple signal routing. A trivial circuit can transmit a qubit from one register to another. That is not a wormhole-like process. A holographic process should hide the information in many-body degrees of freedom and recover it only through the correct global structure. The message should appear to pass through a dual geometry because, on the quantum side, it has been scrambled and then decoded by the appropriate dynamics.

Operator growth is also connected to the possible emergence of black-hole interiors. In some theoretical pictures, increasing complexity and operator size correspond to growth of the wormhole interior. This does not mean that every complex circuit creates space. It means that in special holographic systems, complexity growth may have a geometric dual. Therefore, measuring operator growth on a quantum computer can become a test of whether the model behaves in the expected gravitational way.

The criterion is not simply that the system becomes complicated. Random noise can also make a system complicated. The scrambling must be coherent, unitary, diagnosable, and consistent with the model's predictions. It must preserve quantum information while making it locally inaccessible. This is the black-hole-like signature.

A quantum instantiation of emergent spacetime must therefore show that information is not merely present, but hidden, spread, and recoverable according to a lawlike many-body structure. Scrambling is the dynamical bridge between entanglement and geometry.

11.4 Error-correcting bulk reconstruction

The fourth criterion is error-correcting bulk reconstruction. Holography suggests that bulk spacetime is encoded in boundary quantum degrees of freedom in a manner resembling a quantum error-correcting code. Therefore, a quantum computer claiming to instantiate It from Qubit should show not only entanglement and scrambling, but also protected logical structure.

In a quantum error-correcting code, logical information is distributed across many physical qubits. No single physical qubit contains the whole logical state. The information can survive the loss or corruption of some physical components. In holography, the bulk degrees of freedom play the role of logical information, while the boundary degrees of freedom play the role of physical qubits.

A schematic encoding is:

|logical bulk> -> V -> |physical boundary>

where V is the encoding map. The bulk state is not copied into the boundary in a classical sense. It is encoded nonlocally into the larger quantum system. If the code is good, different boundary regions may reconstruct the same bulk information under appropriate conditions.

This criterion is essential because geometry is not just entanglement. A smooth emergent bulk requires locality, redundancy, and reconstructability. If a quantum processor creates a state in which certain logical degrees of freedom can be recovered from multiple overlapping subsystems, then it begins to display the structure expected of holographic spacetime. The "bulk" becomes a logical layer supported by the entangled boundary hardware.

Error-correcting reconstruction also provides a way to test whether the emergent geometry is more than a visualization. If a claimed bulk operator can be reconstructed from different boundary regions, and if those reconstructions agree operationally, then the bulk has measurable content. It is not merely drawn onto the system from outside.

The strongest experiments would demonstrate that information inserted into an emergent bulk region remains recoverable despite erasures, noise, or partial access, as predicted by the code structure. They would show that logical operators have multiple boundary representations. They would also show transitions in reconstructability corresponding to changes in entanglement wedges.

This criterion links quantum computation directly to spacetime emergence. Fault-tolerant quantum computers already depend on quantum error correction to protect information. Holographic quantum gravity suggests that spacetime itself may be a kind of error-corrected structure. If these two ideas meet experimentally, quantum processors may become platforms not only for computation, but for testing the code-like origin of geometry.

11.5 Area-like entanglement behavior

The fifth criterion is area-like entanglement behavior. In holographic theories, entanglement entropy is not arbitrary. It is related to geometric area. The Ryu-Takayanagi relation expresses this connection in the form:

S_A = Area(gamma_A)/(4*G_N)

For quantum instantiation, the exact gravitational formula need not appear in a small device. But the system should show an entanglement structure consistent with a geometric interpretation. Entropy should scale in a way that resembles boundaries, surfaces, or minimal cuts rather than unrestricted volume-like randomness.

This matters because highly entangled states are common in large quantum systems, but most do not correspond to smooth geometry. A generic maximally entangled state may be too random to define locality. Smooth spacetime seems to require a disciplined entanglement pattern. Neighboring regions should share correlations in a way that supports emergent distance. Entanglement across a boundary should behave differently from entanglement spread without structure.

In tensor-network models, this idea is often visualized through minimal cuts. The entanglement entropy of a boundary region is related to the number or weight of network bonds that must be cut to separate it from its complement. This gives a discrete analog of area:

S_A approximately equals minimal cut through network

A quantum processor could test such behavior by preparing code states or holographic-inspired states and measuring entanglement entropies, mutual information, or related quantities across partitions. If those quantities organize themselves according to an emergent geometry, then the geometry gains operational meaning.

Area-like behavior also helps define emergent locality. In ordinary local quantum field theories, ground states often obey area laws for entanglement. In holography, the area law becomes geometrized through bulk extremal surfaces. If a quantum-computer experiment can show that its entanglement structure maps naturally onto a geometric network, then it approaches the It from Qubit criterion.

However, this must be handled carefully. Many systems have area laws without being gravitational. Area-like entanglement is therefore not sufficient. It becomes powerful when combined with the other criteria: real entanglement, dynamics, scrambling, error correction, reconstruction, and causal consistency. The question is not whether one entropy curve resembles an area. The question is whether a full package of observables points toward geometry.

Area-like entanglement behavior is the metric signature of emergence. It is the place where quantum information begins to look like shape.

11.6 Scaling beyond toy models

The sixth criterion is scaling beyond toy models. Small experiments are valuable, but emergent spacetime is expected to be a collective phenomenon. A three-qubit or nine-qubit circuit can demonstrate a principle, but it cannot settle whether geometry robustly arises from quantum information. The claim becomes stronger only when the relevant behavior survives as the number of degrees of freedom increases.

Scaling matters for several reasons. First, chaos and scrambling become more meaningful in larger systems. Small systems can show information spreading, but they may not display genuine thermalization, random-matrix-like spectral behavior, or black-hole-like scrambling. Second, error-correcting structure becomes more convincing when logical information is protected across many physical qubits. Third, geometric observables such as area, distance, and wedge reconstruction require enough structure to define regions and boundaries.

A useful scaling ladder is:

few qubits -> toy protocol

tens of qubits -> small many-body dynamics

hundreds of physical qubits -> protected logical subsystems

many logical qubits -> robust emergent code geometry

large fault-tolerant systems -> scalable holographic dynamics

At each step, the evidence changes character. A toy protocol can show possibility. A larger many-body system can show robustness. A fault-tolerant logical system can show protected emergence. A scalable holographic simulation can test whether the geometric interpretation becomes better as the system grows.

Scaling also reduces the risk of hand-tuned artifacts. A small model can be designed to produce a desired signal. A large family of systems showing the same behavior under controlled variation is harder to dismiss. The key question is whether wormhole-like teleportation, entanglement wedge reconstruction, operator growth, and area-like entropy improve with scale in the way the theory predicts.

Noise is a major obstacle. Near-term quantum processors suffer decoherence, gate errors, measurement errors, crosstalk, and limited circuit depth. These limitations can mimic, obscure, or destroy the subtle signatures of holographic dynamics. Therefore, error correction is not merely a convenience. It may be necessary for reaching the scale where emergent geometry becomes experimentally meaningful.

Scaling beyond toy models is the criterion that separates suggestive demonstrations from a new experimental physics. The future of It from Qubit depends on whether the effect becomes clearer, not weaker, as quantum systems grow.

11.7 Independent observables and falsifiability

The seventh criterion is independent observables and falsifiability. A claim of quantum instantiation into actual reality must risk being wrong. If every outcome can be reinterpreted as consistent with emergent geometry, then the claim becomes unfalsifiable. A serious It from Qubit experiment must specify which observables should appear, how they should scale, and what results would count against the proposed interpretation.

Independent observables are important because a single successful signal can be misleading. For example, recovering a qubit after a protocol does not by itself prove wormhole-like dynamics. Quantum circuits can recover information for many reasons. The stronger test is whether several independent signatures align: scrambling, coupling dependence, timing windows, operator growth, entanglement structure, reconstruction behavior, thermalization, and complexity growth.

The experiment should therefore make predictions of the form:

If the holographic interpretation is correct, observable X should vary with parameter Y in pattern Z.

For example, the recovery signal might depend on the sign of a coupling. The timing of recovery might track a scrambling time. The entanglement entropy might follow a minimal-cut structure. Operator growth might match chaotic predictions. Reconstruction might succeed from one boundary region and fail from another according to an entanglement wedge transition. Complexity might grow in a way related to a proposed bulk interior measure.

Falsifiability also requires comparison with non-holographic alternatives. A good experiment should ask whether the same observations could be explained by ordinary teleportation, direct circuit routing, weakly chaotic dynamics, commuting Hamiltonians, or classical postselection. The goal is not to force the gravitational interpretation onto the data. The goal is to determine whether the geometric description provides superior predictive organization.

This criterion is especially important because the language of wormholes and emergent spacetime is powerful and easily overextended. A quantum computer can produce beautiful correlations without creating a meaningful geometry. The burden is on the experiment to show that the geometry is doing explanatory work.

A mature field will therefore develop benchmark suites rather than single headline demonstrations. These benchmarks should include entanglement diagnostics, chaos

diagnostics, reconstruction tests, noise robustness, scaling laws, and null models. Only when the holographic interpretation repeatedly outperforms simpler alternatives should the phrase quantum instantiation be used in a strong sense.

Reality requires resistance. A physical instantiation must push back against interpretation by producing observables that could have failed.

11.8 Compatibility with NCT

The eighth and final criterion is compatibility with the Non-Communication Theorem. Any claimed quantum instantiation of emergent spacetime must preserve no-signaling. This is not a minor consistency check. It is the causal boundary of the entire program. If a proposed experiment or theory allows communication through entanglement alone, then it conflicts with the established operational structure of quantum mechanics.

For an entangled system shared by Alice and Bob, Bob's local state is obtained by tracing over Alice's system:

rho_B = Tr_A(rho_AB)

Alice may measure, rotate, or otherwise act locally on her subsystem. But unless Alice sends classical information or introduces an allowed causal interaction, Bob's local statistics cannot change in a controllable way. This remains true even if the entanglement has a geometric interpretation. A bridge generated by entanglement alone must be non-traversable in the signaling sense.

This criterion is especially important for ER=EPR and traversable-wormhole language. A non-traversable bridge is compatible with NCT because it represents connection without passage. A traversable-wormhole-like protocol is compatible with NCT only because it includes additional dynamics, coupling, or classical coordination. The message is not sent by bare entanglement. It is sent through a structured physical protocol.

The same rule applies to quantum computers. If a processor implements a wormhole-inspired teleportation circuit, the transfer must depend on gates, interactions, measurements, and classical processing inside the circuit. There should be no ability for one party to signal by simply choosing a measurement basis on one half of an entangled state. If such signaling appeared, the first assumption should be experimental error, leakage, postselection artifact, or misunderstanding, not a revolutionary violation of NCT.

Compatibility with NCT also shapes the meaning of emergent causality. If spacetime arises from qubits, then light-cone structure cannot be an arbitrary add-on. The emergent geometry must include rules determining which operations can influence which outcomes. No-signaling is

therefore not merely preserved inside spacetime; it may be one of the constraints from which spacetime causality emerges.

The final criterion can be stated simply:

Entanglement may instantiate connection.

Dynamics may instantiate passage.

Classical or causal interaction may instantiate communication.

Entanglement alone may not instantiate a forbidden message.

This is the boundary that keeps the entire program physically disciplined. It allows quantum computers to explore emergent spacetime without abandoning relativity. It allows ER=EPR to propose bridges without producing superluminal telegraphs. It allows It from Qubit to be ambitious without becoming incoherent.

The conclusion of Section 11 is that quantum instantiation into actual reality requires a complete package. Real entanglement is necessary, but not enough. The system must implement dynamics, scramble information, support error-correcting reconstruction, display area-like entanglement behavior, scale beyond toy models, produce falsifiable observables, and remain compatible with the Non-Communication Theorem. Only then can a quantum computer plausibly claim to instantiate not merely qubits, but the first experimentally controlled traces of emergent spacetime.

12. Future Developments: What Would Count as Progress

12.1 Larger and less engineered holographic simulations

The next stage of progress will require larger and less engineered holographic simulations. Early quantum-computer demonstrations are valuable because they show that selected elements of wormhole-inspired teleportation, scrambling, and entanglement dynamics can be implemented in real hardware. But small systems are vulnerable to overinterpretation. A few qubits can display suggestive behavior without possessing the collective structure needed for emergent geometry. A heavily optimized circuit can reproduce a target signal without proving that the signal arises from robust holographic physics.

Future experiments must therefore move from demonstration to scaling. The important question is not simply whether a quantum processor can produce a recovery signal. The question is whether the recovery signal becomes more convincing as the system grows, as the model becomes less hand-tuned, and as independent diagnostics increasingly agree.

Holographic behavior should not depend on one specially selected circuit. It should appear across a controlled class of chaotic, entangled, many-body systems whose dynamics are theoretically connected to gravity-like duals.

A useful progression is:

small optimized circuit -> larger chaotic model -> family of models -> scalable holographic behavior

At the first level, one demonstrates possibility. At the second, one tests whether genuine chaos and scrambling are present. At the third, one asks whether the behavior is robust under changes in Hamiltonian, circuit structure, coupling, and noise. At the fourth, one begins to ask whether the geometric interpretation is not merely suggestive but necessary.

Less engineered simulations will also reduce the risk that the desired result has been built into the experiment by construction. In a strong experiment, the system should be allowed to behave according to its natural many-body dynamics, and the holographic interpretation should emerge from measured observables rather than from post hoc labeling. The more independent features align, the more the interpretation gains force.

This is the expected path from toy models toward physical instantiation. The first quantum-computer wormhole-inspired experiments opened the door. The future will require experiments that are larger, noisier in realistic ways, more chaotic, more diagnostic, and less dependent on delicate selection. Emergent spacetime should become clearer with scale, not disappear when the scaffolding is removed.

12.2 Error-corrected quantum processors

Error correction is likely to be decisive. Near-term quantum devices are limited by decoherence, gate errors, measurement errors, leakage, and restricted circuit depth. These limitations are not minor technical inconveniences. They directly affect the ability to simulate or instantiate the long, coherent, many-body dynamics relevant to holography, scrambling, and emergent geometry.

Holographic physics depends on subtle quantum structure. Scrambling must preserve information while hiding it nonlocally. Teleportation-like recovery must distinguish coherent many-body evolution from noise-assisted artifacts. Error-correcting reconstruction must show that logical information is protected and redundantly encoded. These are precisely the kinds of phenomena that uncontrolled noise can obscure or fake.

Fault-tolerant quantum computation would change the field. Instead of asking how much of a toy model can be compressed into shallow noisy circuits, researchers could implement deeper time evolution, larger logical systems, and more demanding diagnostics. They could test

whether holographic signatures persist over many logical gates. They could compare families of Hamiltonians. They could measure operator growth, entropy structure, and reconstruction behavior with greater confidence.

There is also a conceptual resonance between quantum error correction as an engineering method and holographic quantum error correction as a theory of spacetime. In ordinary quantum computing, error correction protects logical qubits against physical noise. In holography, bulk degrees of freedom appear protected by redundant encoding in boundary degrees of freedom. If future quantum processors use quantum error correction to experimentally instantiate holographic error-correcting codes, the medium and the message will converge: error-corrected machines will be used to test whether spacetime itself is error-corrected quantum information.

The future progression may therefore look like:

physical qubits -> logical qubits -> protected dynamics -> encoded bulk observables -> emergent geometry tests

At each step, the claim becomes stronger. Physical qubits allow entanglement. Logical qubits allow stability. Protected dynamics allow long coherent evolution. Encoded bulk observables allow reconstruction. Emergent geometry tests allow the It from Qubit program to become experimentally disciplined.

Without error correction, the field can still produce suggestive demonstrations. With error correction, it can begin to test whether emergent spacetime is a robust property of quantum information rather than a fragile artifact of small circuits.

12.3 Gravity-mediated entanglement experiments

A separate but complementary path concerns gravity-mediated entanglement. Quantum computers can test holographic models and quantum-information dynamics, but they do not directly prove that gravity itself is quantum. Gravity-mediated entanglement experiments aim at a different target: if two massive objects become entangled through their mutual gravitational interaction alone, then gravity cannot be treated as merely classical under the assumptions of the experiment.

The basic idea is to place two small masses into spatial quantum superpositions and allow them to interact gravitationally. If the only interaction between them is gravity, and if the final state exhibits entanglement between the masses, then the gravitational field must be capable of transmitting quantum information. A purely classical mediator cannot generate entanglement between two initially unentangled quantum systems in the standard framework.

This would not directly prove ER=EPR. It would not show that every EPR pair is a wormhole. It would not demonstrate a traversable bridge or an emergent bulk geometry. But it would be a major step because it would show that gravity participates in the quantum entanglement economy. Gravity would not merely curve a classical background. It would act as a quantum mediator.

The relevance to this paper is clear. The It from Qubit program proposes that spacetime and gravity may arise from quantum information. Holographic simulations test that claim in controlled quantum systems. Gravity-mediated entanglement experiments would test, from the opposite direction, whether gravitational interaction itself has quantum character. If both lines of work succeed, the case for a deep relation between entanglement and geometry becomes stronger.

Such experiments are extremely difficult. They require isolating tiny masses from electromagnetic, thermal, seismic, and environmental noise. They require maintaining spatial superposition in massive systems. They require ruling out non-gravitational channels. They require measuring entanglement without destroying the fragile effect. But their conceptual payoff is large.

The future may therefore divide into two complementary laboratories:

quantum computers -> instantiate qubit-side holographic dynamics

gravity-mediated entanglement experiments -> test whether gravity can generate entanglement

Together, they would attack the same question from opposite ends. One starts with quantum information and looks for geometry. The other starts with gravity and looks for quantum information.

12.4 Complexity growth and black-hole interiors

Complexity growth is another expected frontier. In quantum information, complexity measures how difficult it is to prepare a state or implement an operator from simple ingredients. In black hole physics, complexity has been proposed as a possible dual of interior growth. The rough intuition is that while the exterior black hole may appear settled thermally, the interior bridge may continue to grow. On the quantum side, the corresponding state may continue to grow in circuit complexity.

This idea is attractive because entanglement entropy alone may not capture the full interior of a black hole. Entanglement can saturate while the interior continues to grow. Complexity offers a candidate quantity for this continuing growth. If the ER bridge length or volume is related to quantum complexity, then quantum computers may become direct experimental tools for studying a simplified version of black-hole interior dynamics.

A schematic relation sometimes considered is:

complexity growth <-> interior growth

This should not be read as an established universal law. It is a research direction. But it gives quantum computers a natural role because they are built from circuits. They can prepare states with known gate histories, implement chaotic dynamics, and measure proxies for operator growth and circuit complexity. They may allow experimental tests of whether complexity behaves as predicted in holographic models.

The challenge is that complexity is hard to measure. Exact circuit complexity is generally computationally difficult to determine. Experiments must use proxies: operator size, scrambling diagnostics, recovery difficulty, sensitivity to perturbation, or statistical features of evolved states. These proxies must be interpreted carefully. A complicated noisy circuit is not the same as holographic complexity growth. The complexity must be coherent, structured, and connected to the theoretical model.

Progress in this area would mean showing that complexity-related observables scale with time, system size, and perturbations in a way matching black-hole-inspired predictions. It would also mean distinguishing complexity growth from ordinary decoherence or random noise. This is another reason error-corrected processors matter. Long coherent circuits are needed to separate true complexity growth from hardware degradation.

If successful, this direction would extend It from Qubit beyond static geometry. It would suggest that not only spatial structure, but also interior spacetime development, may have a quantum-information description. The “It” would include not only surfaces and bridges, but the growth of hidden regions whose physical meaning is encoded in quantum complexity.

12.5 Testing whether geometry is emergent or merely interpretive

One of the most important future tasks is to distinguish emergent geometry from interpretive geometry. A geometric picture can be useful without being physically instantiated. Physicists often use diagrams, analogies, and mathematical transformations that do not imply new ontology. The It from Qubit program must therefore answer a hard question: when is geometry real, and when is it merely a convenient language?

A geometric description becomes more than interpretive when it generates successful, independent, and falsifiable predictions. It must organize observables better than non-geometric alternatives. It must explain relations among entanglement, entropy, reconstruction, causality, complexity, and dynamics that would otherwise appear disconnected. It must survive perturbations and scaling. It must constrain what can and cannot happen.

For a quantum-computer experiment, the following would count as stronger evidence for emergent geometry:

entanglement entropy follows area-like behavior

bulk-like information is reconstructable from boundary regions

operator growth matches geometric expectations

teleportation recovery depends on coupling and timing as predicted

complexity proxies track interior-growth predictions

causal constraints remain consistent with NCT

the same geometric model predicts multiple independent observables

By contrast, the following would suggest merely interpretive geometry:

a single recovery signal without independent diagnostics

a model so small that chaos cannot be meaningfully established

a circuit hand-tuned to produce a desired output

no scaling behavior

no error-correcting reconstruction

no distinction from ordinary teleportation or direct routing

a geometric story applied only after the data are known

The difference is not semantic. It determines whether quantum computers are testing quantum gravity or merely illustrating it. An illustration can be valuable pedagogically, but instantiation requires more. The geometry must become an experimentally constrained emergent structure of the device.

This distinction also protects the field from exaggerated claims. Saying that a quantum processor instantiated a holographic model is not the same as saying it created a macroscopic wormhole. Saying that a state has a geometric dual is not the same as saying that laboratory space has been punctured by a bridge. The correct claim must be precise: the processor physically realized quantum dynamics whose best theoretical description includes an emergent bulk geometry.

Future progress will be measured by how much of that sentence becomes experimentally unavoidable.

12.6 Why NCT remains the boundary condition

The Non-Communication Theorem remains the boundary condition for every future development. No matter how far the field advances, no successful theory can allow entanglement alone to transmit a chosen message faster than light. This is not a conservative prejudice. It is built into the operational structure of quantum mechanics and repeatedly confirmed by experiment. Any apparent violation would require extraordinary scrutiny and would more likely reflect leakage, hidden communication, postselection, or faulty interpretation.

NCT is especially important because the language of wormholes, bridges, and emergent spacetime naturally tempts the imagination toward forbidden shortcuts. If entanglement is a bridge, why not send a message through it? If a quantum computer simulates a traversable wormhole, why not treat it as faster-than-light communication? If spacetime emerges from qubits, why should ordinary causal limits remain?

The answer is that viable emergent geometry must include viable emergent causality. Geometry without causal discipline is not physical spacetime. A bridge that exists only as correlation is non-traversable. A traversable protocol requires additional permitted interactions. A teleportation process requires classical information or an equivalent causal resource. The rule is stable:

bare entanglement -> no signal

entanglement plus allowed operation -> possible protocol

protocol plus causal side information -> usable communication

This boundary is not a weakness of ER=EPR or It from Qubit. It is what makes them compatible with relativity. If entanglement can contribute to spacetime geometry, then NCT explains why that contribution does not destroy light-cone structure. It separates connection from communication. It allows the universe to be nonlocally correlated without becoming causally incoherent.

In future quantum-computer experiments, NCT should be treated as a diagnostic principle. If a claimed wormhole-like process appears to work without the required coupling, measurement, or classical information, the result should be suspect. If the process works only when the full causal protocol is supplied, it is consistent with quantum mechanics. The strongest experiments will not bypass NCT; they will display it in a new geometric language.

Thus the Non-Communication Theorem is not merely a constraint at the edge of the paper. It is the central law that ties the paper together. EPR creates the puzzle. Bell proves the nonclassical correlation. Teleportation operationalizes the resource. ER=EPR geometrizes the relation. It

from Qubit generalizes the emergence. Quantum computers instantiate the dynamics. NCT preserves causality at every step.

12.7 Final synthesis: entanglement can build geometry, but not a forbidden message

The future of this field will likely be shaped by a disciplined synthesis. Entanglement is real. Bell tests establish that nature contains correlations beyond local classical explanation. The Non-Communication Theorem establishes that those correlations cannot be used by themselves to send messages. Quantum teleportation shows how entanglement becomes operational only when paired with classical information. Attosecond studies show that entanglement formation can have local time structure. ER=EPR proposes that entanglement may have a geometric face. Holography gives mathematical machinery for turning quantum information into spacetime. It from Qubit proposes that the "It" of geometry may arise from qubits, codes, and entanglement. Quantum computers may become the first machines capable of physically instantiating and testing this chain.

The central expectation is not that a near-term device will open a visible wormhole. The more realistic expectation is that quantum processors will increasingly instantiate model systems whose measured observables are best described using emergent geometry. These observables may include scrambling, entropy-area behavior, teleportation dynamics, error-correcting reconstruction, operator growth, and complexity. If these features scale together, the case for emergent spacetime will become stronger.

The deepest future development would be convergence among three lines of evidence. First, quantum computers would show robust holographic dynamics in controllable many-body systems. Second, gravity-mediated entanglement experiments would show that gravity itself can participate in quantum entanglement. Third, theory would explain how causal spacetime emerges from quantum error-corrected entanglement while preserving NCT. Such convergence would not merely add another chapter to quantum information theory. It would change the meaning of spacetime.

The final claim of this paper is therefore cautious but ambitious. Entanglement may be more than a resource inside spacetime. It may be part of the substrate from which spacetime is built. Quantum computers may be more than tools for calculation. They may become physical workbenches for testing how qubits, entanglement, and code structure generate geometry. But the same rule remains absolute: no emergent bridge, no EPR pair, no holographic code, and no quantum processor can turn bare entanglement into a forbidden message.

The proper slogan is not that entanglement abolishes distance. It is that entanglement may explain distance. It may build connection, encode geometry, generate reconstructable bulk structure, and illuminate the quantum origin of spacetime. But it does so under the discipline of

non-communication. The universe may be more deeply connected than classical physics imagined, yet its connections are not arbitrary channels. The “It” may arise from the qubit, but the qubit remains governed by causality.

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